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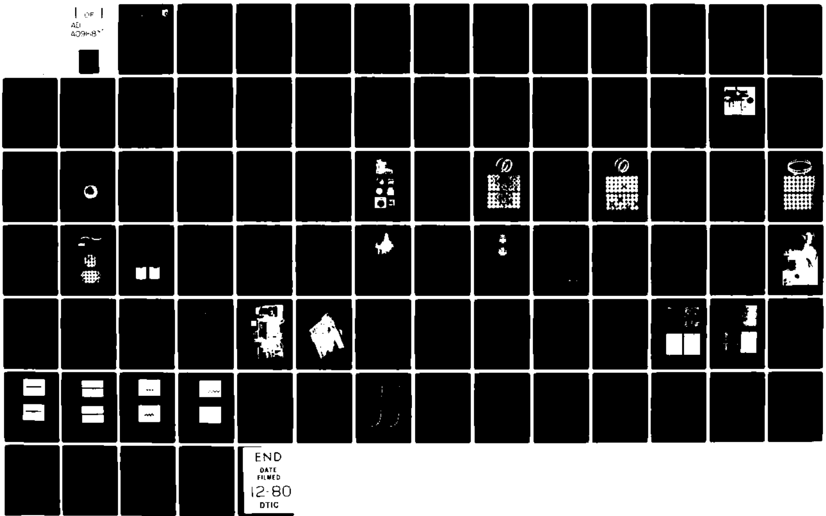

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IMPROVED CAPABILITIES TO DETECT INCIPIENT BEARING FAILURES

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A methodology using safe, low level radiation technique for the detection of wear in gas turbine engine mainshaft bearings has been developed and evaluated in a simulated gas turbine engine bearing environment. In conjunction with spectrometric analyses of engine oil samples, the radioactive tag will detect low levels of wear and will simultaneously indicate whether the tagged bearing is the source of the wear. Iron-55 is employed as the active tag owing to its low radiation levels, long half-life, and homogeneity of the isotope in the bearing rollers. The low levels of radiation existent in the tagged wear particles requires the separation of wear debris from the oil. Test results showed

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that the tagging method would provide a means of identifying the tagged rollers experiencing abnormal wear at the ±0.5 part per million iron level. Safe, low-level radioactive bearing roller tagging was achieved by waiting six months after neutron irradiation for the decay of the iron-59 and the chromium-51 gamma emitting radioisotopes. Wear measurements are conducted using the long half-life, low energy emitting X-rays from iron-55. The technique used for tagging, debris concentration, debris measurement, and bearing testing is given.

PREFACE

This report describes the work performed by the Pratt & Whitney Aircraft Group/Government Products Division of United Technologies Corporation, West Palm Beach, Florida, under U. S. Air Force Contract F33615-78-C-2008. The report covers the period from 1 May 1978 to 31 March 1980.

This program to study "Improved Capabilities to Detect Incipient Bearing Failures" in the aircraft turbine engine environment was sponsored by the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL/POSL) Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 304806 and Work Unit 30480602, with H. A. Smith and P. W. Centers, AFWAL/POSL as Project Engineers. J. A. Alcorta was the P&WA Program Manager. Evaluation of the radioactive methods was conducted at United Technologies Research Laboratories under the direction of L. L. Packer, Chief of the Radioisotope Laboratory. The testing and evaluation of the tagging technique at simulated turbine engine operating conditions was conducted at P&WA by J. H. Mohn.

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SECTION I

INTRODUCTION AND SUMMARY

Current Air Force operational procedures employ analyses of engine oil to detect abnormal wear of gas turbine oil wetted parts including mainshaft bearings. The technique employed to conduct these analyses is the Spectrometric Oil Analyses Program (SOAP). However, since SOAP does not determine the location at which wear occurs in the turbine engine, supplemental techniques such as radioactive tagging of a mainshaft bearing and associated analysis of the wear metal debris can pinpoint the location of the distressed bearing. Additionally, the technique can detect low levels of wear in critical bearings that SOAP analysis would not disclose.

The objective of this program was to develop and evaluate techniques for the detection of initial wear of turbine engine mainshaft bearings, to provide information as to the location of such distress and to demonstrate the methods in a simulated turbine engine environment.

The program consisted of five tasks. Task I comprised an evaluation of radioactive methods to tag mainshaft bearings and identify and count wear debris. In Task II, the bearing system used in the demonstration was determined, and the bearings were procured. Task III provided for the inspection of the selected bearing before and after tagging to assay the effects of the tagging on the metallurgical properties of the bearing alloys. The procedures used in the selected method were developed and demonstrated under Task IV, in which the selected bearing system was tagged and tested at simulated turbine engine operating conditions. The safety and handling considerations of the selected methods were evaluated and the cost/benefit ratios for applying the selected method were assessed in Task V.

Specifically, the initial work determined the radioactive tag, the tagging method, the nuclear counting methods and the wear metal debris recovery technique. Safety and handling considerations resulting from the radioactive nature of this program were addressed as part of the decision process and the bearing system in which the techniques were tested was defined.

The principal work undertaken during the second half of the program consisted of a successful demonstration of the tagging technique in a simulated turbine engine operational environment and investigations into the effects of the tagging technique on the metallurgical properties of M50 bearings steel. A life cycle cost benefit analysis which indicates a positive benefit was also performed. Additional effort was directed at the refinement of the debris recovery and nuclear counting techniques including the calibration of the nuclear counting system.

The primary findings of the program are:

(1) Radioactive Tagging Method

Iron-55 was chosen as the active tag due to the low radiation levels, long half life, and the homogeneity of the isotope in the bearing rollers. The neutron activated bearing material has revealed a linearity between nuclear counting and the parts per million concentration of oil-borne roller debris in the oil. This provides a means of recognizing distress in the tagged bearing. Alternate tagging methods examined included impregnation by krypton-85. Gaseous diffusion of krypton-85 was not considered acceptable, as the penetration into the bearing surface of this

isotope was not deep enough to permit the detection of high speed roller bearing wear. However, krypton-85 impregnation might be acceptable for large, shallow wear measurements or in materials more porous than bearing steels.

(2) *Radioactive Tag Demonstration Test Program*

A state-of-the-art high speed roller bearing was selected for the neutron irradiation tagging technique demonstration program. Two individual bearings were tagged and tested separately in a simulated turbine engine bearing operating environment. Each test was structured by bearing modification and test conditions to produce a specific bearing wear regime. Test results showed that the tagging technique would provide a means of identifying initial wear of a tagged bearing.

(3) Wear Metal Debris Recovery

Due to the low level of radiation in the bearing tagging technique, separation of wear metal debris from the lubricating fluid is required. The low level radioactive debris is filtered from the oil using membrane filtration in the 0.5 to 1 micron range. Membrane filtration was used due to its high recovery efficiency and its simplicity of use. In addition, membrane filters deposit the wear metal debris on the filter surface, thereby permitting the direct incorporation of such debris into a nuclear counting system.

(4) Nuclear Counting Methods

Literature and instrument surveys showed that a gas flow proportional system for beta emissions and x-ray counting constitutes the most suitable low-level radioactivity measuring technique for both neutron-irradiation and krypton-impregnated bearing material. Sophisticated systems with cosmic guard detectors and background shielding to reduce environmental radiation are commercially available. Repeatable measurements in the picocurie range are attainable.

(5) Neutron Irradiation Effects on Metallurgical Properties

All nondestructive and destructive metallurgical characterization testing as well as available literature indicate that no metallurgical or structural changes in the M50 material were induced as a result of the low level irradiation process required for the Iron-55 bearing tag. Non-destructive and destructive pre- and post-irradiation metallurgical characterization including investigations into hardness, grain size and carbide distribution as well as ultrasonic, eddy current and flourescent penetrant inspections were unable to distinguish any variation between pre- and post-test results. A literature survey also indicates that the test bearing rollers were irradiated to a test fluence at least 10^4 times lower than that known to induce metallurgical or structural property change.

(6) Government Regulations — Radiation Safety

The amount of radioactivity present on the test rollers was limited to a level that did not impose any direct contact handling restriction during roller inspection, assembly, and installation. A "CAUTION": Radioactive Material" tag and inventory control were the only Nuclear Regulatory Commission NRC regulations applicable during the test program. Disposition of used rollers by a licensed disposal company will be required. No restrictions on the used oil are required.

(7) Life Cycle Cost Benefits

The radioactive tagging technique is applicable to any engine/roller bearing system. As part of the development program a life cycle cost estimate was conducted based on an advanced P&WA turbofan engine bearing system. A comparison of acquisition costs for the tagging technique with the savings of operational/support costs of the technique as they are applied to the selected engine/bearing system results in a positive savings of over 4 million dollars.

Engine modularization has become an integral part of aircraft engine design to help achieve the goals of reducion in maintenance costs and engine down time. The radioactive bearing tagging technique herein described complements this modularization by defining an engine diagnostic system that will identify specific engine bearings experiencing above normal wear rates, thereby confining the amount of teardown to the particular bearing compartment in which the problem is located. Further, the detection capability of the system has been enhanced to permit identification of roller bearing wear distress in order to avoid unscheduled engine shutdowns.

SECTION II

RADIOACTIVE TAGGING METHODS

1. TAGGING FOR AIRCRAFT ENGINE MAINTENANCE

Presently the Air Force routinely analyzes engine lubricants under the Spectrometric Oil Analysis Program (SOAP). SOAP permits the detection of incipient breakdowns in the oil-wetted sections of turbine engines through the analysis of oil-borne wear metal debris. This technique permits the removal of engines prior to secondary damage; however, extensive inspection of nearly all oil-wetted engine parts is required in order to locate the damaged component.

A diagnostic method utilizing radioactive tagging of key engine mainshaft bearings, in conjunction with SOAP analysis, overcomes this limitation. By pinpointing the location of a problem bearing in the engine, radioactive tagging would eliminate or significantly diminish the extent of teardown. Accordingly, maintenance costs and engine down time would be reduced.

Radioactive techniques have been previously used to measure wear on bearings. Engine wear metal debris measurements utilizing radioisotope excitation for x-ray fluorescence has been employed by Pratt & Whitney Aircraft (P&WA) Group, Reference 1, to measure iron concentrations in oil systems. This system correlated well with SOAP techniques and achieved a standard deviation accuracy of ± 3 parts per million (ppm). However, the system involves the use of an inflight electronic package which requires further refinement before it will be practical for normal maintenance procedures. Bearing wear tests were conducted (References 2 and 3) using reactor irradiation of rolling elements with radioactive iron as the active material. Although significant measurement accuracies were attained (SKF Industries attained repeatable wear measurements of 3×10^{-10} g/1000 revolutions, Reference 2), the radioactivity levels were high, 100 to 200 millicuries (mCi), Reference 3. Radiation levels of this magnitude are unacceptable for engine maintenance procedures. Levels approximately a thousand times lower are required when using radioactive iron isotopes in order to minimize safety and handling problems.

The use of kryptoalloys for temperature measurement studies has been extensively pursued by the United Technologies Research Center (UTRC) over the last decade. Kryptoalloys are solids into which a radioactive isotope of krypton have been incorporated. The temperature measuring technique has also been applied by P&WA and UTRC to investigate metal temperature in various engine turbine vanes and blades. Such investigations have been conducted on TF30 turbine blades after 150-hr engine endurance testing, on ATEGG turbine blades, as well as on the metal surfaces of JT9D No. 3 ball bearing elements.

While developmental work has been carried out utilizing the previously discussed radioactive techniques, the long term field use of such techniques for specific bearing component oil debris identification has not been investigated. This program incorporated a very low level radioactive technique to detect bearing wear in a simulated gas turbine engine oil system.

The practical constraints of introducing radioactive tagging of engine mainshaft bearings within the Air Force operational environment includes consideration of safety, handling, and maintenance procedures, as well as consideration of engine oil sample processing logistics. These constraints established the following criteria used in determining the optimum radioactive levels of the proposed methods:

1. Radioactive Half-Life

To provide off-the-shelf capabilities, the radioactive half-life of the isotope selected for the tagging program should be in excess of two years and should be activated to provide failure detection and location information for a period of no less than five years. These periods are approximately the mean time between overhauls of operational aircraft. At each overhaul interval, the bearings could then be replaced with reactivated tags for an additional five year period.

2. Radioactive Emissions/Amount of Radioactivity

The amount of radioactivity present must be minimized to simplify handling procedures using the proposed method for turbine engines operated in the Air Force environment. Due to the low microcurie levels of radioactivity under consideration, the techniques will require only minimal restrictions on the direct material contact handling when assembling, installing, or inspecting the bearings. In order for such a situation to exist, the levels of radioactivity realized in the technique must not be considered environmentally significant under the Nuclear Regulatory Commission Rules and Regulations (Reference 4) exemption provisions.

3. Bearing Metallurgical Properties

Standard bearing handling, cleaning, and surface protection procedures must be strictly adhered to during the bearing material tagging process. The tagging procedure must not affect the metallurgical characteristics of the bearing steel.

4. Tagged Surface Area

The method used to tag the bearing material must be capable of incorporating the radioactive tag over the roller surface to a depth commensurate with that necessary to provide failure detection and location information.

2. NEUTRON IRRADIATION

A. General

Radioactive iron tagging for measuring the wear rates of oil-wetted components has been used on automotive engines (Reference 5) and on rolling element bearings (References 2 and 3). Reactor neutron irradiation of the predominantly iron-containing engine components produces both iron-59 (45 day half-life) and iron-55 (2.6 year half-life). The iron-59 had been selected as the primary radiotracer in previous investigations because its gamma ray emissions of 1.1 and 1.29 Mev are easy to detect, both during engine operation and in oil samples recovered from the engine. Iron-55 decays by electron capture and emits low energy 5.9-kev X-rays. The 2.6 year half-life and the low energy X-ray emissions, make iron-55 a sensitive long-term M50 alloy bearing tag.

Subjecting premium quality bearing steels such as M50 to a neutron flux in a reactor results in the transmutation of various constituents of the material to radioactive isotopes.

The amount of radioactivity induced in bearing material is a function of the weight percent of each element comprising the alloy, the isotope percentage of the reacting isotopes, the activation cross-section and the neutron flux. The specific activity of isotopes produced as a result of reactor irradiation can be calculated from the equation:

$$A = \sigma \phi N (1 - e^{-0.693t/T}) \qquad (1)$$

where:

A = specific activity (dis/sec g)
σ = thermal neutron cross section for the (n, γ) reaction (cm^2)
ϕ = thermal neutron flux (n/cm^2 sec)
N = number of target atoms per gram of iron (g^{-1})
t = irradiation time (days)
T = half-life of radioisotope (days)

Of the elements comprising the M50 composition (Table 1), only iron, chromium, and cobalt convert upon irradiation into radioactive isotopes with a half-life of sufficient duration to be of interest in this program. Table 2 shows the technical details regarding the neutron irradiation of M50 bearing steel.

The only major uncertainty of the iron-55 tagging procedure is the byproduct generation of cobalt-60. Cobalt appears in M50 bearing steel as a contaminant. Cobalt-60 generation is analytically determinable and is a function of irradiation flux, exposure time, and the cobalt content of the M50 material. (Economic considerations are currently reducing the high-value cobalt content in the iron scrap used in M50 steel production.) For a given irradiation flux/exposure time requirement the cobalt-60 generation could be controlled by using master melt information to select material having a certain maximum cobalt content.

The half-life of iron-55 is of sufficient duration to permit the decay of the high concentration of iron-59 and chromium-51 isotopes to insignificant levels within six months after removal from the reactor. Table 3 shows the decay factors of the various isotopes both six months and five years after removal from the reactor. Figure 1 depicts the radioactive decay of the iron-55.

TABLE 1. M50 BEARING STEEL COMPOSITION AND HEAT ANALYSIS FOR BEARINGS USED IN TEST PROGRAM

	P&WA Specification 725		*Emission Analysis*[1]	
Constituent	*Min Weight Percent*	*Max Weight Percent*	*Test Bearing No.1 Weight Percent*	*Test Bearing No. 2 Weight Percent*
Iron	87.92	90.58	88.84	89.28
Molybdenum	4.00	4.50	4.31	4.29
Chromium	3.75	4.25	4.25	4.15
Vanadium	0.90	1.10	1.05	0.93
Carbon	0.77	0.85	0.82	0.83
Manganese	-	0.35	0.35	0.28
Cobalt	-	0.25	0.01	0.01
Silicon	-	0.25	0.23	0.17
Tungsten	-	0.25	0.02	0.03
Nickel	-	0.15	0.06	<0.01
Copper	-	0.10	0.05	<0.01
Phosphorus	-	0.015	0.006	0.008
Sulfur	-	0.015	0.006	0.005

[1]Melt emission analysis supplied by bearing vendor

TABLE 2. NEUTRON IRRADIATION DATA FOR M50 TEST BEARINGS

Element:	*Nominal Weight Percent In M50*	*Percent Isotopic Abundance for Activation*	*Activation Reaction*	*Cross-Section (Barns)*[1]	*Half-Life*	*Gamma Ray Emission (keV)*
Chromium	4	4.35	$^{50}Cr\,(n,\gamma)\,^{51}Cr$	15.9	28 days	320
Iron	89	0.31	$^{58}Fe\,(n,\gamma)\,^{59}Fe$	1.14	45 days	143 1098 1290
	89	5.8	$^{54}Fe\,(n,\gamma)\,^{55}Fe$	2.2	2.6 years	5.9[2] 6.5
	89	5.8	$^{54}Fe\,(n,p)\,^{54}Mn$ [3]	0.68	291 days	5.4[2] 835
Cobalt	0.0025[4][5]	100	$^{59}Co\,(n,\gamma)\,^{60}Co$	37	5.2 years	1170 1330

[1] Thermal neutron cross section (Reference 6)
[2] X-rays
[3] Requires 1 MeV or greater neutron energies (Reference 7)
[4] W% cobalt = 0.0025 as determined by cobalt -60 gamma spectrum analysis using NBS SRM 4215-F
[5] Present in the M50 as a contaminant to a maximum concentration of 2500 ppm.

TABLE 3. M50 RADIOISOTOPE DECAY FACTORS

	Time After Reactor Removal		
Radioisotope	*0*	*0.5yr*	*5yr*
Iron-55	1.0	0.875	0.264
Iron-59	1.0	0.0623	0.0
Cobalt-60	1.0	0.9362	0.518
Chromium-51	1.0	0.0116	0.0
Manganese-54	1.0	0.659	0.0154

B. Iron-55 Irradiation Tagging

(1) Initial Radioactive Tagging of Bearing Roller Samples by Neutron Irradiation

To assess the effects of minor M50 alloy constituents on the tagging procedure, specifically cobalt, and to provide tagged bearing material for wear metal debris recovery testing, six engine roller bearings (16 by 16 mm) and 90 milligrams of abraded bearing material (No. 600 silicon carbide paper) were irradiated at the Union Carbide swimming pool reactor in Tuxedo, New York during April 1978. The irradiation was conducted at a thermal flux of approximately 1.6×10^{10} neutrons/cm^2-sec for 157 hours and was completed on 14 April 1978.

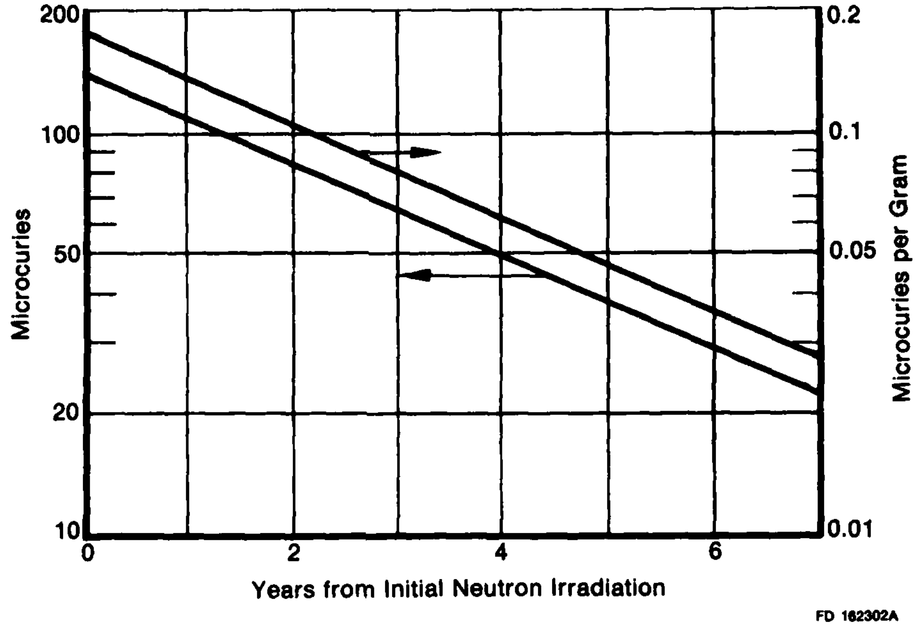


Figure 1. Iron-55 Radioactivity Levels for Test Program

The amounts of radioactive iron-55 and iron-59 per gram of M50 bearing material produced by the 157 hour irradiation are presented in Table 4 as a function of time after removal from the reactor. The radioactivity levels from the actual irradiation are 20 times greater than iron-55 irradiation projected for the rig tests in the verification task of the program. The initial irradiation was conducted at a level higher than the minimum required for detection in order to provide greater sensitivity during the debris recovery laboratory evaluation and to determine the possible presence of elements not included in the M50 P&WA specifications.

Gamma ray spectroscopic measurements of two neutron-irradiated rollers were performed on 17 July 1978, and again on 29 September 1978, 93 and 165 days following the removal of the rollers from the reactor. A lithium-drifted Germanium detector was employed; six distinct gamma ray energy peaks from the irradiated material were apparent. Thermal neutrons produced radioisotopes of iron-59 (1098 and 1290-keV gamma rays) and chromium-51 (320-keV gamma ray), as well as the long half-life cobalt-60 (1170- and 1330-keV gamma rays). In addition, the fast neutron flux produced an 835-keV gamma ray from manganese-54. This 291 day half-life manganese-54 originates from a fast-neutron proton reaction with iron. Figure 2 depicts the spectra for both sets of measurements. The short half-life of chromium-51 and iron-59 is evident. The fast neutron reaction of stable iron-54 which produces radioactive manganese-54 (^{54}Fe (n,p) ^{54}Mn) occurs at neutron energies in excess of 1 MeV. The Union Carbide swimming pool reactor used for the neutron irradiation was estimated to have a fast flux of 1×10^9 neutron/cm^2-sec for an estimated thermal to fast flux ratio of 15.

(2) Radioactive Tagging of No. 4 Bearing Roller Sets by Neutron Irradiation

Neutron irradiation of two bearing roller sets was performed at Georgia Institute of Technology's 5 megawatt heavy water research reactor located at the Neely Research Center. The bearing material was positioned in a vertical thimble (V-43) located in the reactor graphite reflector. The reactor was operated at 250 kilowatts specifically for the bearing roller irradiations used. The nominal thermal flux at the V-43 location was 1.4×10^{11} neutrons/cm^2-sec., the nominal fast flux (energy greater than 0.1 MeV) was 4×10^9 neutrons/cm^2-sec.

TABLE 4. M50 BEARING STEEL RADIOACTIVITY DUE TO THE 14 APRIL 1978 NEUTRON IRRADIATION

(157 hr at Thermal Neutron Fluxes of 1.6×10^{10} neutrons/cm^2 sec)

	Microcuries Per Gram[1]			
Time After Neutron Irradiation	*0*	*½ yr*	*1 yr*	*5 yr*
Iron-55	3.59	3.14	2.75	0.95
Iron-59	1.58	0.10	0.005	0.000
Cobalt-60[1]	0.14	0.13	0.120	0.080
Manganese-54	0.19	0.12	0.080	0.002
Chromium-51	20.5	0.20	0.070	0.000
Total Activity	26.00	3.69	3.025	1.032

[1] Calculated values (Ref. 6)

[2] Used atomic absorption measurements of 370 ppm cobalt from a material analysis performed during this program

To establish the irradiation time necessary to induce an iron-55 activation of 0.145 microcuries per gram, an initial 60 minute irradiation was performed on the drilling material from roller number A12 taken from test bearing No. 1 (Ref. Section III.2.c). Neutron irradiation of the iron contained in the roller produces both iron-55 and iron-59 isotopes. The iron-59 emits a distinct 1098 keV gamma ray, as shown in Figures 2 and 3. This 1098 keV gamma ray is interference free and was used to determine the iron-59 activation induced during the 60 minute irradiation. A ratio of 1.7 between iron-55 activity and iron-59 activity was calculated (Eq. 1) to assess the quantity of iron-55 activity. The intensity of the 1098 keV iron-59 gamma-ray was measured using a lithium-drifted germanium detector on 8 June 1979. The detector was calibrated using a National Bureau of Standards Certificate Standard Reference Material 4215-F "Mixed Radionuclide Gamma-Ray Emission-Rate Point-Source Standard." An iron-59 activation of 0.069 microcuries per gram was measured. The resulting iron-55 activation would be 0.117 microcuries per gram. The iron-55 activation attained under the short irradiation times used is linear with time, therefore, an irradiation time of 77 minutes would be required to produce the desired iron-55 activity of 0.145 microcuries per gram. Table 5 details the bearing roller neutron irradiation information and Table 6 specifies the radioactive tagging levels of the bearing roller sets.

As expected the manganese-54 fast neutron reaction that occurred during the initial radioactive tagging of roller samples at Union Carbide's swimming pool reactor (Figure 2), was not evident from the Georgia Tech's heavy water reactor irradiation (Figure 3). The graphite reflector position used to irradiate the roller bearing sets had a thermal flux to fast flux ratio of 350. This resulted in the elimination of the manganese-54 reaction as a significant aspect of this program.

3. KRYPTON-85 DIFFUSION IMPREGNATION

A. General

The impregnation of radioactive krypton-85 gas into engine hardware for the purpose of obtaining postoperative measurement of maximum surface temperature distribution has been in use by Pratt & Whitney Aircraft Group since 1968 (References 8, 9, 10, and 11). The majority of the work has involved 1st- and 2nd-stage turbine blades and vanes; temperature data have been recovered from rig-operated TF30 mainshaft bearings. Maximum temperature data have been recovered from TF30 turbine blades after 150 hours of engine endurance testing. Current laboratory work is aimed at defining the accuracy of the method on JT9D gas turbine mainshaft bearing test pieces over the 250 to 450°F temperature range. Additional work in this area has been reported by other investigators (Reference 12).

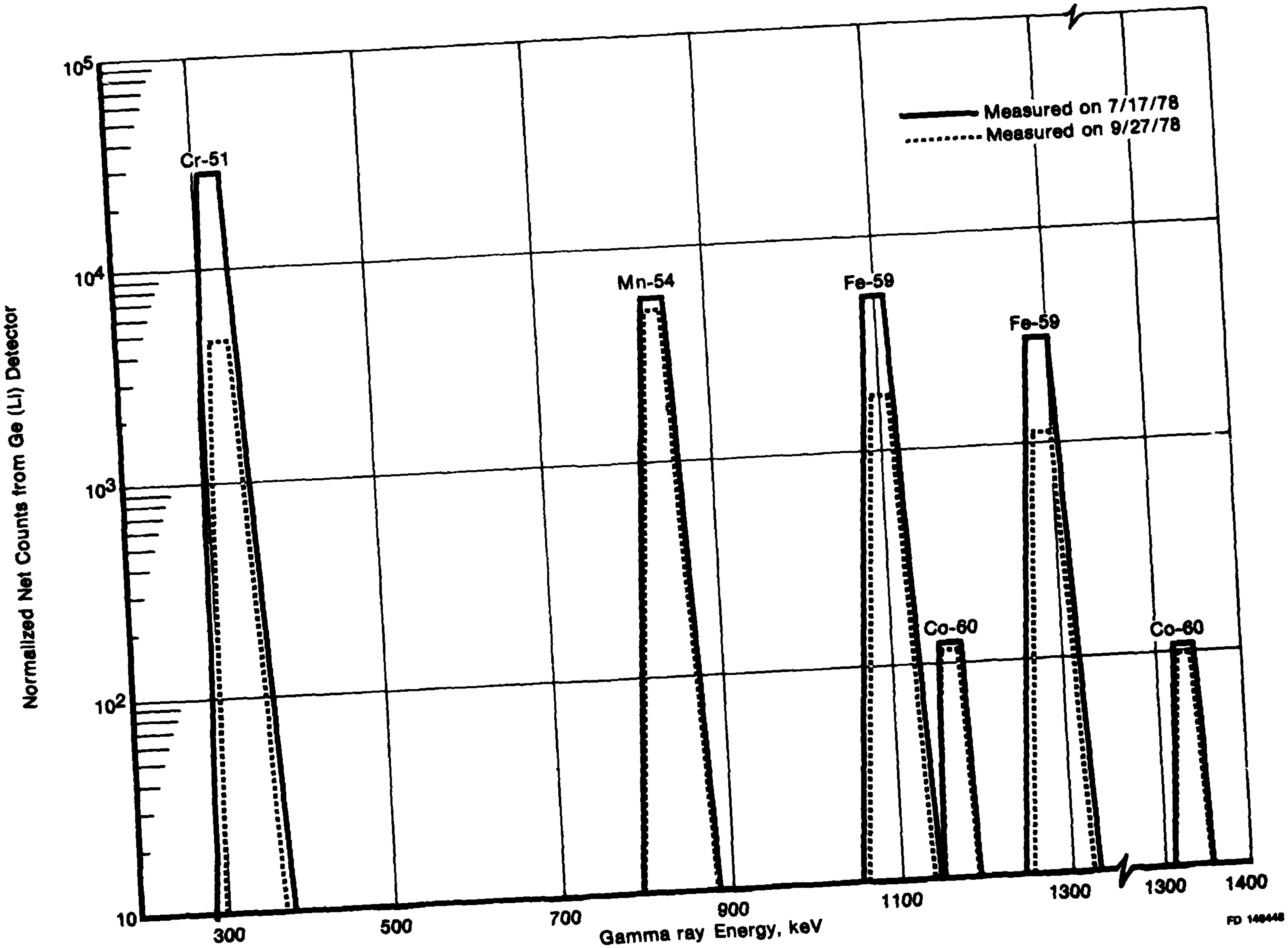


Figure 2. Gamma Ray Spectra from Initial Neutron Activation of M50 Roller Bearing Material at Union Carbide Pool Reactor

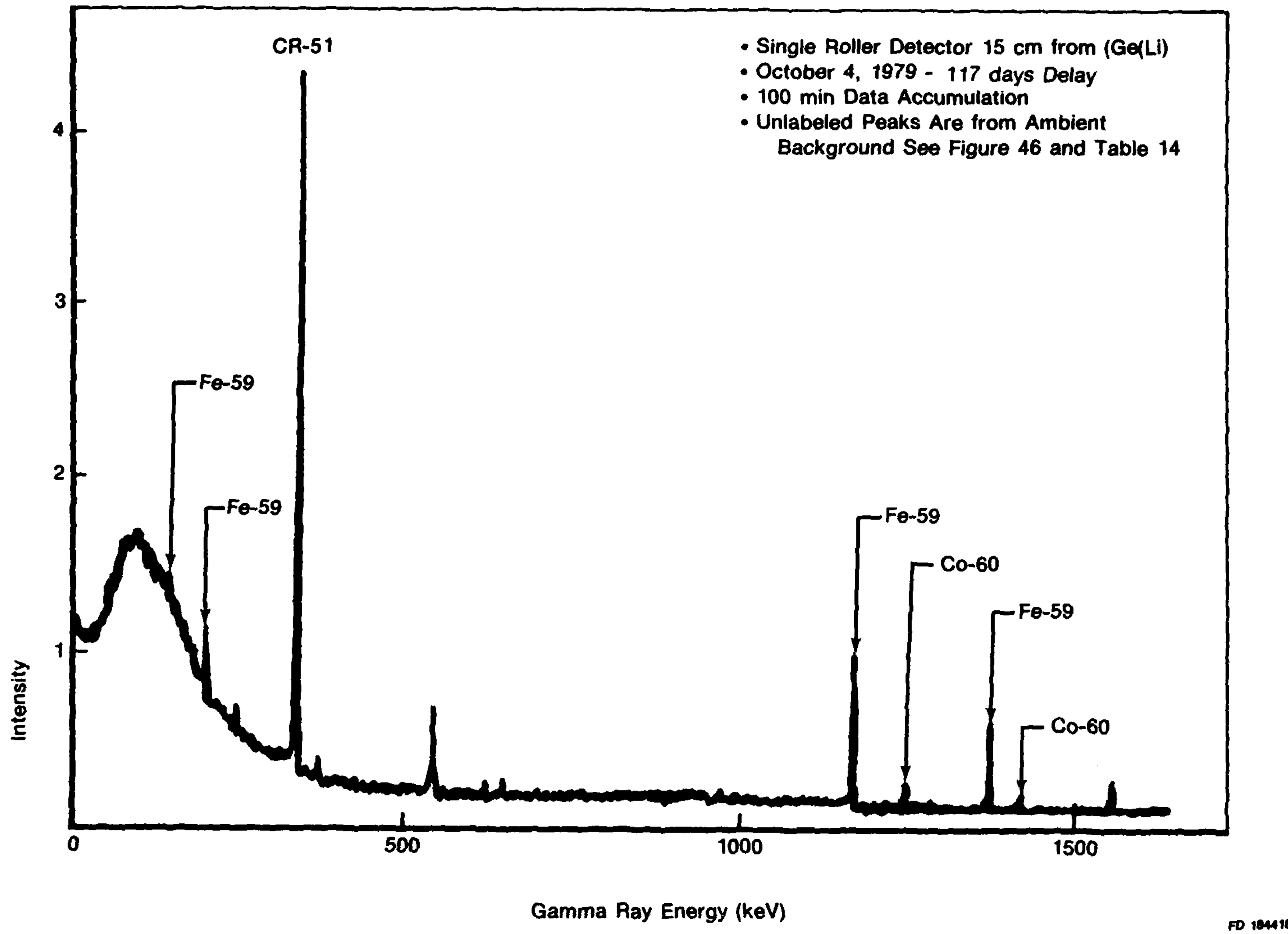


Figure 3. Gamma Ray Spectra from M50 Bearing Material Irradiated at Georgia Institute of Technology's Heavy Water Reactor

TABLE 5. TEST BEARING ROLLER SETS IRRADIATION INFORMATION

Bearing Material Sample	Date	Irradiation Time (min)	Iron-55 Microcuries/gram
1. 93.4 mg of drilling from No. 12 roller Test Bearing No. 1	June 7, 1979	60	0.117
1. 32 rollers Test Bearing No. 1	June 8, 1979	77	0.145
2. 103 mg of drilling from No. 30 roller Test Bearing No. 1			
3. 2 extra rollers (metallurgical characterization samples)			
1. 32 rollers Test Bearing No. 2	June 18, 1979	87[1]	0.164
2. 64.7 mg drilling material from No. 18 roller Test Bearing No. 1			
3. 70.9 mg drilling material from No. 24 roller Test Bearing No.1			
4. 2 extra rollers (metallurgical characterization samples)			

[1]Unintentional overrun o. 10 minutes.

TABLE 6. RADIOACTIVE TAGGING OF BEARING ROLLER SETS[1]

Decay Time (yr)	Bearing Mass (g)	Iron-55[4] (μCi)	Iron-59 (μCi)	Cobalt-60[2] (μCi)	Chromium-51[4] (μCi)	Total System Activity (μCi)	Activity of One ppm[3] (μCi)
0	800	129	75	0.5	1145	1350	0.03
	1	0.16	0.094	0.00063	1.43	1.69	
0.5	800	113	4.56	0.46	12.8	131	0.003
	1	0.14	0.0057	0.00058	0.016	0.162	
1	800	99	0.24	0.44	0.16	99.8	0.0022
	1	0.12	0.0003	0.00055	0.0002	0.121	
5	800	32		0.26		32.26	0.0007
	1	0.04	0	0.0003	0	0.04	

(1)1.4 × 10^{11} n/cm^2-sec thermal flux for 82 minutes (average of the two radiation times, Table 5)
(2)W% Cobalt = 0.0025 as determined by cobalt - 60 gamma spectrum analysis using NBS SRM 4215-F
(3)1 ppm = 0.018 gm in a 5-gal oil system
(4)Determine by calculation using NBS SRM 4215-F iron-59 and cross section data, Reference 6.

The application of krypton-85 to the measurement of wear rates has been attempted with the impregnation of electroplated nickel (Reference 13). A nickel surface was applied in rotary-sliding motion against a surface of nickel-free tool steel. The wear process was then carried out under water in order to prevent the loss of nickel dust. The nickel loss was determined by wet chemical analysis of both the containing water and the steel face. The results revealed an exponential decrease in residual krypton radioactivity as a function of the nickel mass removed from the surface. These measurements demonstrated that the krypton had penetrated to a depth in excess of 3×10^5 Å (1.2×10^{-3} in.) and that the amount of trapped krypton decreased with depth. No attempt was made to measure the radioactivity of the nickel-wear metal debris. Work was also reported in reference 13 regarding the depth of krypton-85 penetration in alloy steel rollers. This was determined by a series of electropolishing and residual radioactivity measurements. The krypton depth was determined to be on the order of 2×10^4 Å (8×10^{-5} in.) and exhibited an exponential decrease with depth, as previously found in the electroplated nickel results.

The 10.6 year half-life of krypton-85 and its nearly pure beta emission of 695-keV energy electron result in a radioactive tag with a minimum radiation hazard, but with sufficient electron energy to produce a measurable wear metal debris tag. The U. S. Nuclear Regulatory Commission (NRC) regulation permits 100 μCi of krypton-85 to be exempted from all NRC regulation. A neoprene sheet 0.032-in. thick will provide about 95% attenuation of the beta radiation exposure. The 0.4% emission of the 514-keV gamma from krypton-85 is at a low, nonhazardous level.

B. Impregnation Procedure

Impregnation of fifteen 16 by 16 mm bearing rollers was performed at the United Technologies Research Center (UTRC) krypton-85 facility (Figure 4). Introduction of radioactive krypton-85 gas into solids was accomplished by exposing the solid to a high temperature, high-pressure krypton environment. Krypton diffusion into the material increases exponentially with temperature, but linearly with pressure and with the square root of time exposure. The thermal diffusion of the krypton was carried into the M50 rollers at 450°F and 320 psia for 267 hours. The krypton gas mixture contained 13.4 percent krypton-85 gas, while the remaining atmosphere constituted inert nonradioactive krypton gas.

Prior to impregnation, the rollers were solvent cleaned using standard bearing cleaning procedures to remove the oil protective coating and were oxide-passivated by heating in air for 4 hours at 500°F. Seven of the impregnated rollers were new, while eight rollers were previously run in a gas turbine engine environment. The used rollers were also treated electrochemically by following a standard preplating cleaning procedure (alkaline cyanide solution — ENDOX 214) to remove the residual varnish coating.

Radioactive assay subsequent to impregnation revealed a level of 0.5 to 0.8 μCi per new roller and a range of 1.2 to 1.6 μCi per used roller. The higher levels for the used rollers can be attributed to the krypton retention in the residual varnish layer.

When the kryptonated material is reheated to temperatures lower than its previous maximum temperature, no significant activity losses occur. The maximum temperature endured by the kryptonated material must be maintained for a sufficient period to liberate the krypton atoms having binding energies less than, or within the range of kinetic energy distributions at the maximum temperatures. Thus, in order to thermally "stabilize" the krypton impregnated bearing material for temperatures in excess of those existing for engine oil operating conditions, the rollers were thermally stressed in a 450°F oil bath prior to depth measurements. The stabilization process consisted of subjecting the rollers to twenty-four 4 minute heating and cooling cycles. Approximately 10 percent of the initial krypton radio-

activity was lost during this process. Prior work has shown that operating at temperatures lower than 450°F will result in negligible additional gas loss.

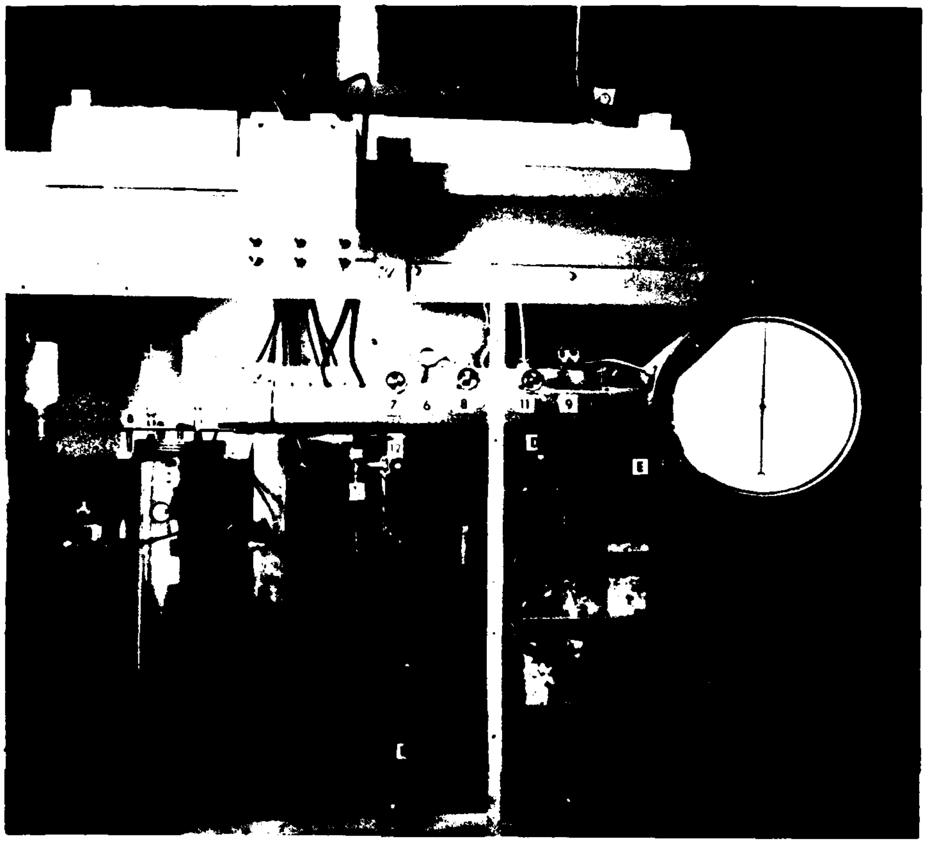


Figure 4. Radioactive Krypton Impregnation Facility at UTRC

C. Depth Measurements

The depth penetration of the gas, as well as the concentration and distribution of depth into the parent material are dependent upon the nature of the material being impregnated. The trapping sites for the stable retention of krypton atoms appear to be associated with defect structures in the grain boundaries and intergranular defects of the host material. Chemical and physical properties of the parent material were not found to be altered by the impregnation of the krypton gas into the surface (Reference 12).

The depth of krypton diffusion was measured by sequential abrading and electropolishing removals. Nuclear counting was performed on the end surface area of the various rollers. Two rollers were investigated for each material removal technique. A plastic scintillator coupled to a photomultiplier tube was used to measure the residual radioactivity. The amount of bearing material removed was determined by weighing the rollers before and after each material removal. Figure 5 shows that the fraction of residual (I) activity after material removal divided by the initial activity (I_o), reached the 0.01 level at a depth of about 2 μm (0.08 mils). The abrasive removal depth measurements reached the 0.01 level at a depth of about 1.9 μm. Both the abrasive removal and electropolishing removal data are presented in

Figure 5. The 0.001 I/I_0 level was determined to be about 3 μm (0.118 mils). Krypton activity at less than the 0.001 I/I_0 level would not contribute to bearing tagging detection sensitivity. Measurements of the abraded material removed from the silicon carbide paper confirmed that the krypton was retained in the removed debris.

The electropolishing technique consisted of masking a 0.495 cm^2 area on the roller end and then dipping approximately two-thirds of the roller surface into an insulating lacquer. The roller was then electrically connected to form the anode, a platinum strip providing the cathode. A 10% solution of perchloric acid in methanol constituted the electrolytic solution. The solution was maintained at −10°F through the use of liquid nitrogen cooling. Electropolishing was performed with an open circuit voltage of 25v DC and about 0.3 amps for periods of both 10 and 25 seconds.

Krypton-85 diffusion tagging does not penetrate to a sufficient depth in the M50 bearing material to be applicable to the identification of high-speed roller bearings eccentric end wear. The roller eccentric end wear is restricted to less than 10 percent of the total surface area of a roller with the wear in this area attaining several mils in depth. Figure 6 shows the wear pattern on a 16-mm roller exhibiting heavy end wear. This wear pattern represents a mass loss of about 12 mg or 0.67 ppm in a 5-gal system. In addition, due to the exponential depth distribution of the krypton gas, a correlation between activity and wear metal debris (parts per million) cannot be accomplished. The krypton tag will solely identify the wear location.

The krypton-85 tagging concept would be applicable for larger surface wear areas in which 0.1 mils of surface depth represents a significant amount of wear.

4. CONCLUSIONS — RADIOACTIVE TAGGING

The neutron irradiation of bearing material is recommended for bearing failure detection tagging procedures. Two radioisotopes, krypton-85 and iron-55, have been assessed as possible tags in this program. Of the two, iron-55 was selected for use in radioactive tagging for the monitoring of end wear on high speed roller bearings. The reasons for this selection follow.

Both a literature survey and experimental testing were conducted on krypton-85 prior to its rejection for use as a radioactive tag. The major limitation of the krypton-85 isotope is its inability to penetrate to sufficient depths in the bearing material to be applicable for the identification of high-speed roller bearing eccentric end wear. Additionally, since krypton-85 diffusion concentrations are exponential with depth in the bearing material, this tag cannot be used to determine the proportion of material loss from the affected bearing.

In contrast to krypton-85, iron-55 meets a number of important criteria as a radioactive tagging isotope:

a. The radioactivity levels in neutron-activated iron are uniform throughout the material and can be established at a specific value.

b. Wide range of iron-55 radioactivity, spanning tenths of microcuries to millicuries can be achieved by varying either the neutron flux or the irradiation time.

c. In addition, the iron-55 tagged wear metal debris radiation characteristics remains identical to the parent tagged roller and is not influenced by the operational environment.

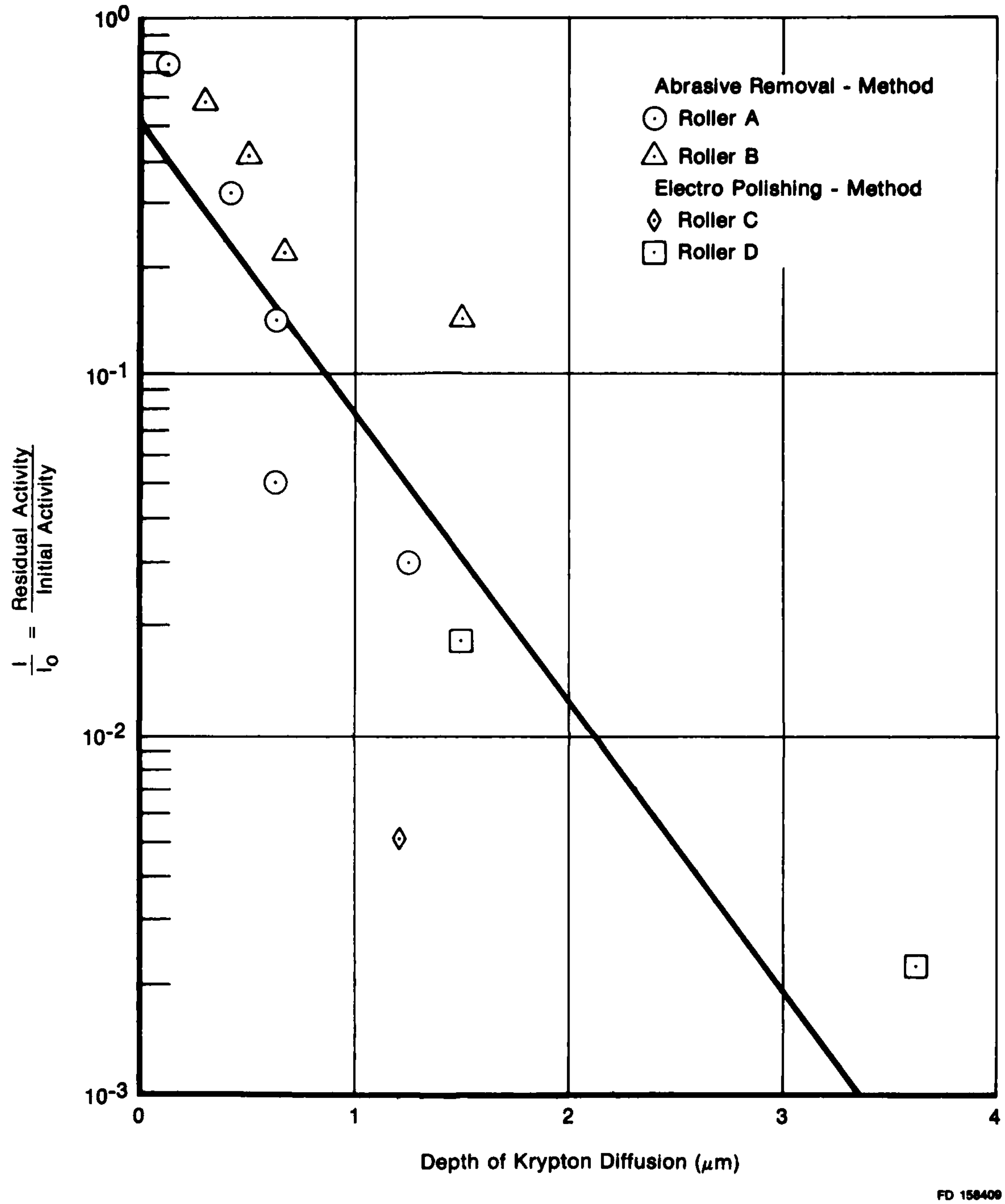


Figure 5. Krypton-85 Depth Penetration Into M50 Bearing Material — Abrasive and Electropolishing Removal Data

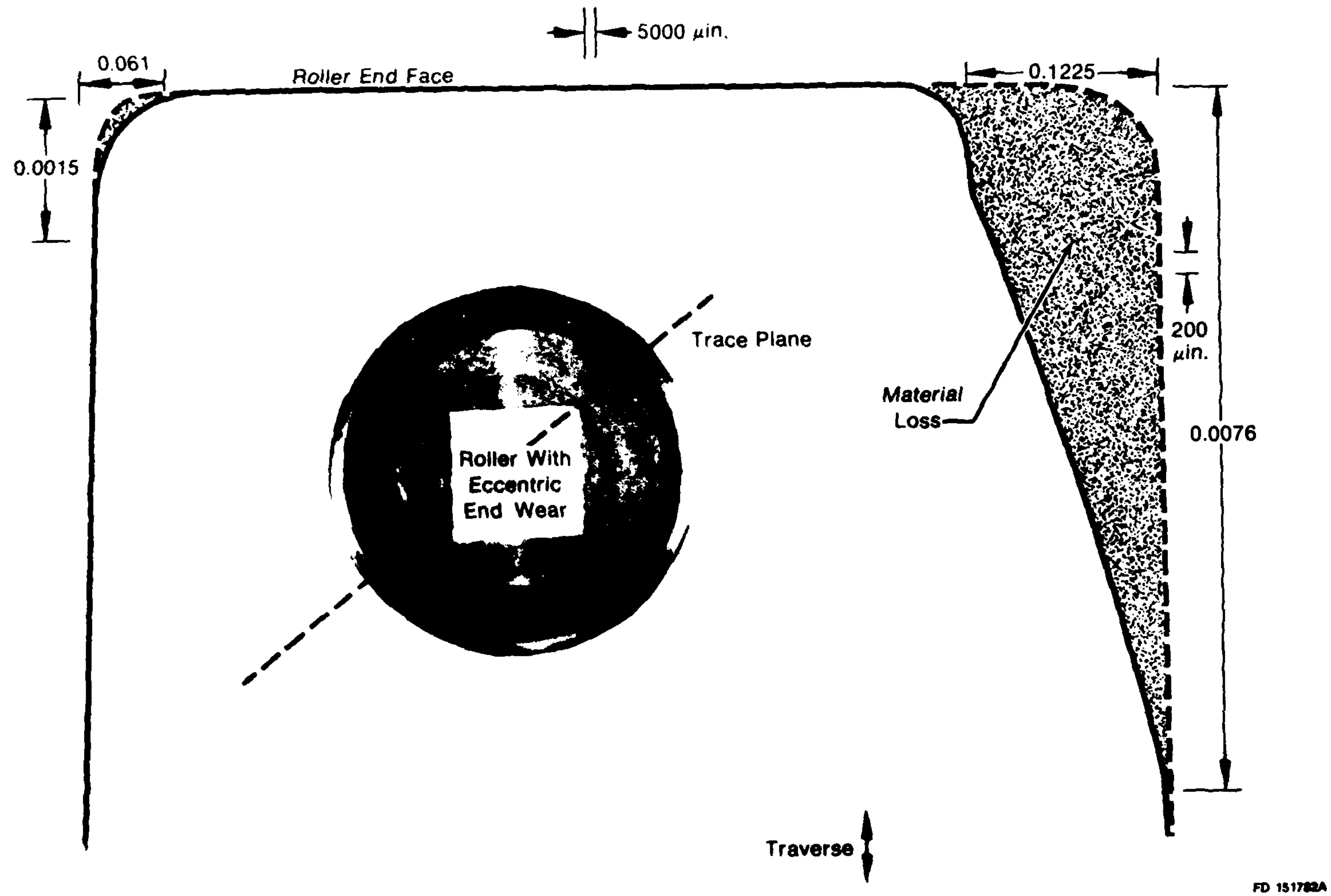


Figure 6. Wear Depth Trace of a Roller Exhibiting Eccentric End Wear

d. Finally, as shown in the nuclear measurement section (v), the assay of neutron-activated bearing material incorporating iron-55 has revealed an assayable linear relationship between nuclear counting and the parts/million concentration of iron debris in a lubricating fluid. Thus, not only does the iron-55 isotope provide a means of recognizing the occurrence of distress in the tagged bearing, but it furnishes as well a method of quantifying the amount of material loss from that bearing.

The only disadvantage to the use of iron-55 as a radioactive tag results from the by-product generation of the contaminant, cobalt-60. Since cobalt-60 generation is analytically determinable, and experimentally controllable, this minor disadvantage is not prohibitive.

Therefore, as a result of the advantages of the iron-55 isotope noted above, and because of its adherence to all tagging criteria, iron-55 has been selected as the radioactive tag best suited for utilization in this program.

SECTION III

RADIOACTIVE TAG DEMONSTRATION TEST PROGRAM SUMMARY

1. SUMMARY

Two neutron irradiated state-of-the-art test bearings (refer to Section II) were subjected to a simulated gas turbine engine bearing environment.

This bearing was selected for this program for the following reasons:

a. Its wear characteristics have been extensively studied both analytically and experimentally.

b. Test rigs were available, making it a cost effective method to evaluate the tagging technique.

The purpose of this test program was to determine if the neutron irradiation tagging procedure would:

a. Detect initial bearing roller wear.
b. Isolate the location of a distressed roller bearing.

Each bearing was individually tested in a program incorporating bearing modification and operating conditions to produce a specific bearing wear regime.

Test Bearing No. 1 Modifications to the bearing geometry and test conditions imposed were designed to produce the moderate amount of roller wear debris associated with roller eccentric end wear.

Test Bearing No. 2 Modifications to this bearing and the operating parameters were designed to produce the relatively large amounts of wear debris which result from severe bearing distress caused by both the progression of advanced eccentric end wear to cage cross rib fracture, and by roller to roller O.D. contact.

Prior to each test, and at 15-to-20 minute run-time intervals, oil samples were collected from the test bearing oil scavenge system. These oil samples were subjected to absorption and emission SOAP procedures and to radiological evaluation (Section V). In each oil sample set the radiological tagging technique indicated that the irradiated rollers experienced a marked increase in wear rate at a critical point in time. These data agree with the results obtained utilizing the conventional oil-borne iron detection techniques. Additionally, the shape of the graphs generated in each case indicates the bearing wear regime.

2. RADIOACTIVE TAG DEMONSTRATION TESTS

A. Test Bearing Selection Criteria

Engine modularization achieves goals of reduced maintenance costs and engine down time. The radioactive bearing tagging technique utilizes this modularization by defining an engine diagnostic system that will identify bearings with above normal wear rates, thereby reducing the amount of teardown to the specific bearing compartment in which the problem bearing is located.

The selected bearing is among the highest DN (bore diameter x speed) bearings in the Air Force inventory and is inaccessible for inspection or removal without core module teardown. The cylindrical roller bearing with an operating DN of 2.2×10^6, in conjunction with a thrust bearing, supports the high shaft of the engine's core module. The basic bearing geometry is shown in Figure 7. Knowledge of the location of a bearing experiencing above normal wear would reduce the engine operational support costs through a reduction in maintenance cost and engine down time. This bearing was selected for the study because extensive knowledge of this bearing's wear characteristics was amassed through a comprehensive analytical and rig evaluation program, and the proven ability to induce wear through various means on this bearing made it a cost-effective method to evaluate the tagging technique.

B. Roller Bearing Wear

The higher thrust-to-weight ratios required for advanced military aircraft turbine engine designs demand advanced technology bearings. These high technology engines require: (1) high shaft speeds to achieve maximum gas dynamic performance, minimum size, and minimum weight, (2) flexibile bearing support structures for lightweight and minimum flowpath obstructions, and (3) large shaft diameters for high bending and torsional stiffnesses. High DN bearings with high bearing misalignment capability are necessary to meet these engine goals.

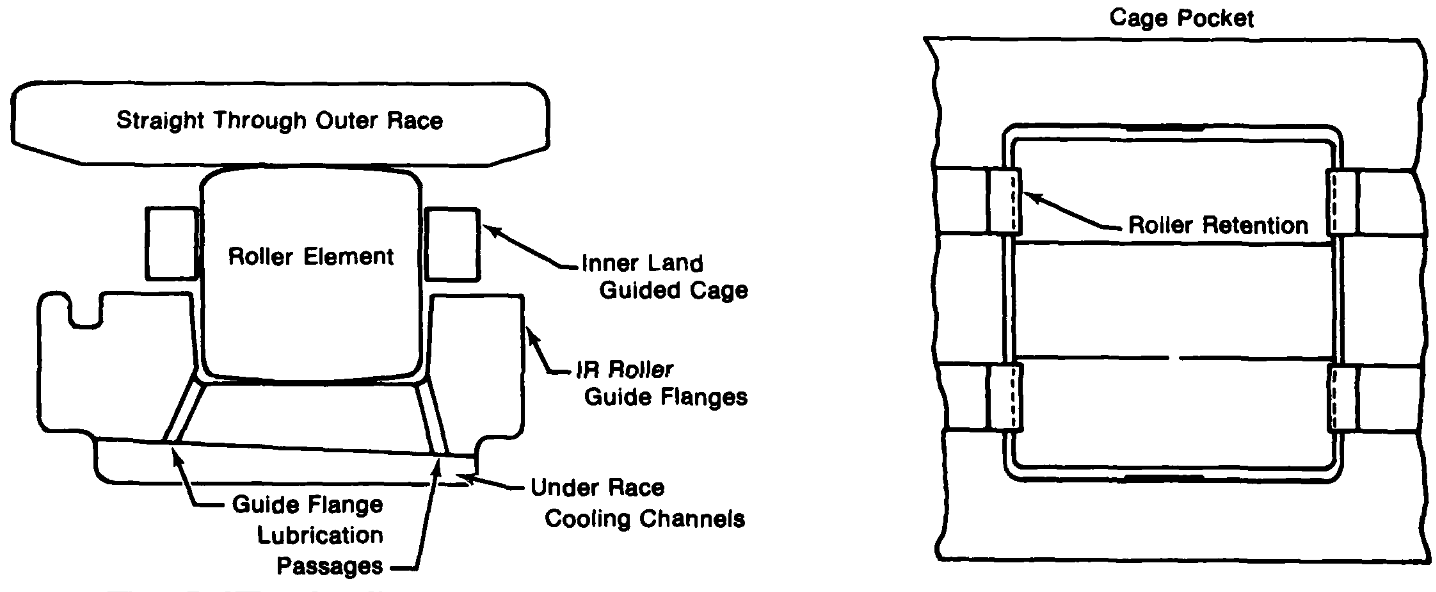
The increased engine rotational speeds and the resultant increase in DN levels have intensified the influence of geometric variations on roller dynamics, causing an increase in roller susceptibility to distress. Evidence accumulated in the field and data obtained in development tests have led to the conclusion that roller dynamic behavior at high DN is not fully understood, although recent investigations are providing insight to the problem. Roller instabilities occur frequently in high DN bearings. The characteristic distress mode which identifies roller instability and skewing is rapid eccentric wear on the end surfaces of one or more of the rolling elements of a bearing. Figure 8 shows the eccentric type wear pattern on one end of various rollers in a variety of high-speed environments, the other end having a similar pattern. This condition can exist undetected until bearing malfunction occurs. Evidence accumulated in the field and data obtained in development tests have indicated that roller bearing distress as shown in Figure 8 is common to all sizes of high speed roller bearings and is caused by roller instabilities.

C. Modifications to the Test Bearing for Accelerated Wear

Experimental evaluations of high speed cylindrical roller bearings have shown that roller unbalance, increased internal clearance, and geometrical variations such as end clearance, roller-to-guide-rib contact height, and roller dynamics are the most important drivers in high speed roller bearing eccentric end wear. (Reference 14.)

The test bearing rollers were modified prior to irradiation to ensure the desired distress mode in the rig. Two different levels of wear were intentionally introduced.

Test bearing No. 1 was modified by unbalancing four rollers to a level of 6000 mg-mm^2. Additionally, the bearing free state internal clearance was increased to 0.0113 in. (approximately twice the blueprint nominal value) to accelerate the wear rate. The unbalance was induced by drilling 0.081 in. holes in the ends of the rollers to a depth of 0.124 in., as shown in



Inner Race Bore dia:	165 mm
Basic Roller Size, L/D:	16 mm x 16 mm
No. of Rollers:	32
No. of Radial Lube Holes:	2 per Side
Bearing Material:	M50

Cage Material: AMS 6414
Cage Plating: Silver per AMS-2412

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Figure 7. Basic Geometry of the Cylindrical Roller Bearing Used in the Test Program

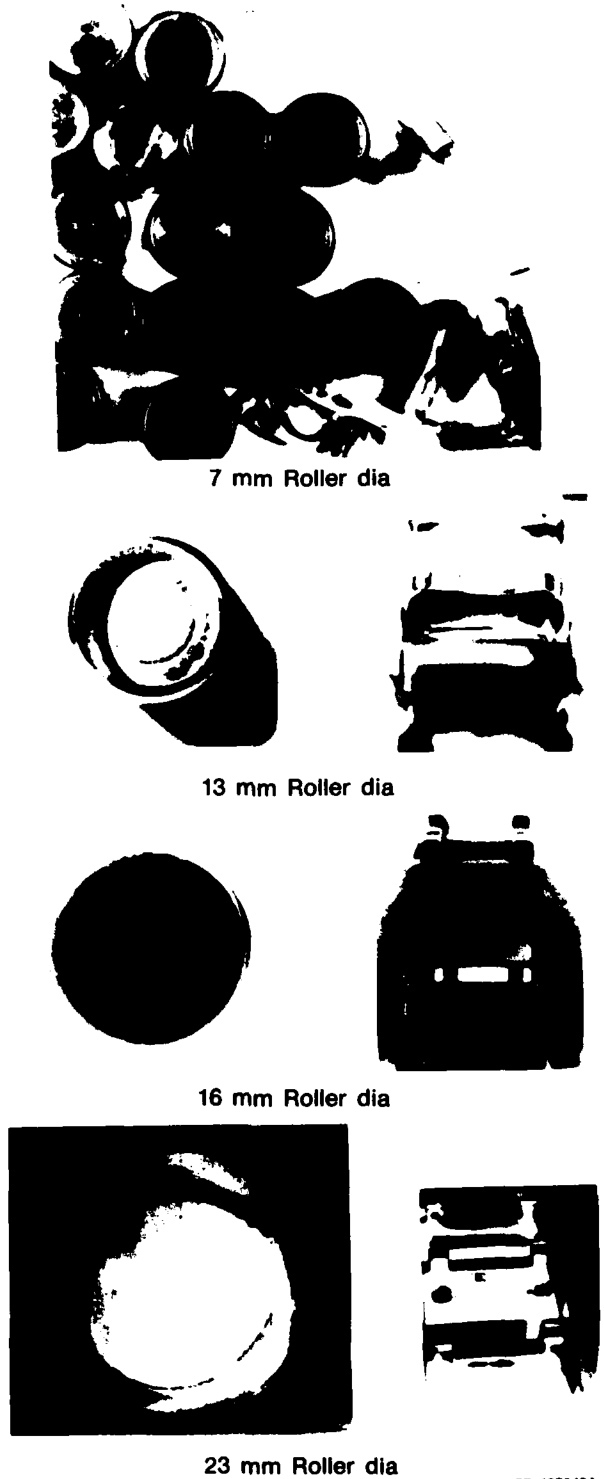

Figure 8. Application Showing Eccentric End Wear in High Speed Roller Bearings

Figures 9 and 10. These bearing modifications were designed to produce during the course of the first ten hour rig test, heavy roller eccentric wear.

Roller end nonuniformities, such as eccentric end wear, i.e., a variation in wear depth around the roller ends, are required for wear to progress to cage fracture. Once the cross rails have fractured, the rollers rub against one another, thereby producing larger quantities of radioactive wear debris.

The advanced stage of eccentric end wear distress which precedes cage fracture was duplicated in the second rig test by modifying the end face of four rollers from ***test bearing No. 2*** (per Figures 11 and 12). This was done to obtain both a high level of roller unbalance (5100 mg-mm^2) and roller to cage guide rib contact. Additionally, the bearing free state internal clearance was also increased (IRC = 0.0081 in., B/P Nom 0.0058 in.) to accelerate the wear rate.

D. Test Program To Simulate Gas Turbine Engine Bearing Operating Condition

Two separate tests were conducted to experimentally evaluate the neutron irradiation tagging technique as a means of detecting incipient bearing failure. Each test involved a different test bearing. Both tests were structured by test bearing modification and test condition to simulate in a gas turbine engine environment a distinct bearing wear mode and rate. Prior to each test the lubrication system and internal test rig surfaces were thoroughly hot flushed with clean MIL-L-7808G lubricant which was continuously filtered through 10μ depth type filters.

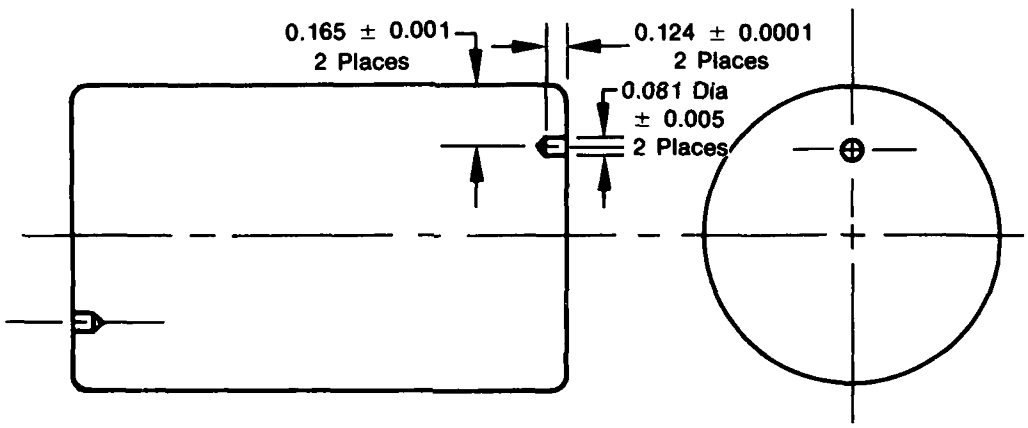

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Figure 9. Modified Test Roller Bearing No. 1

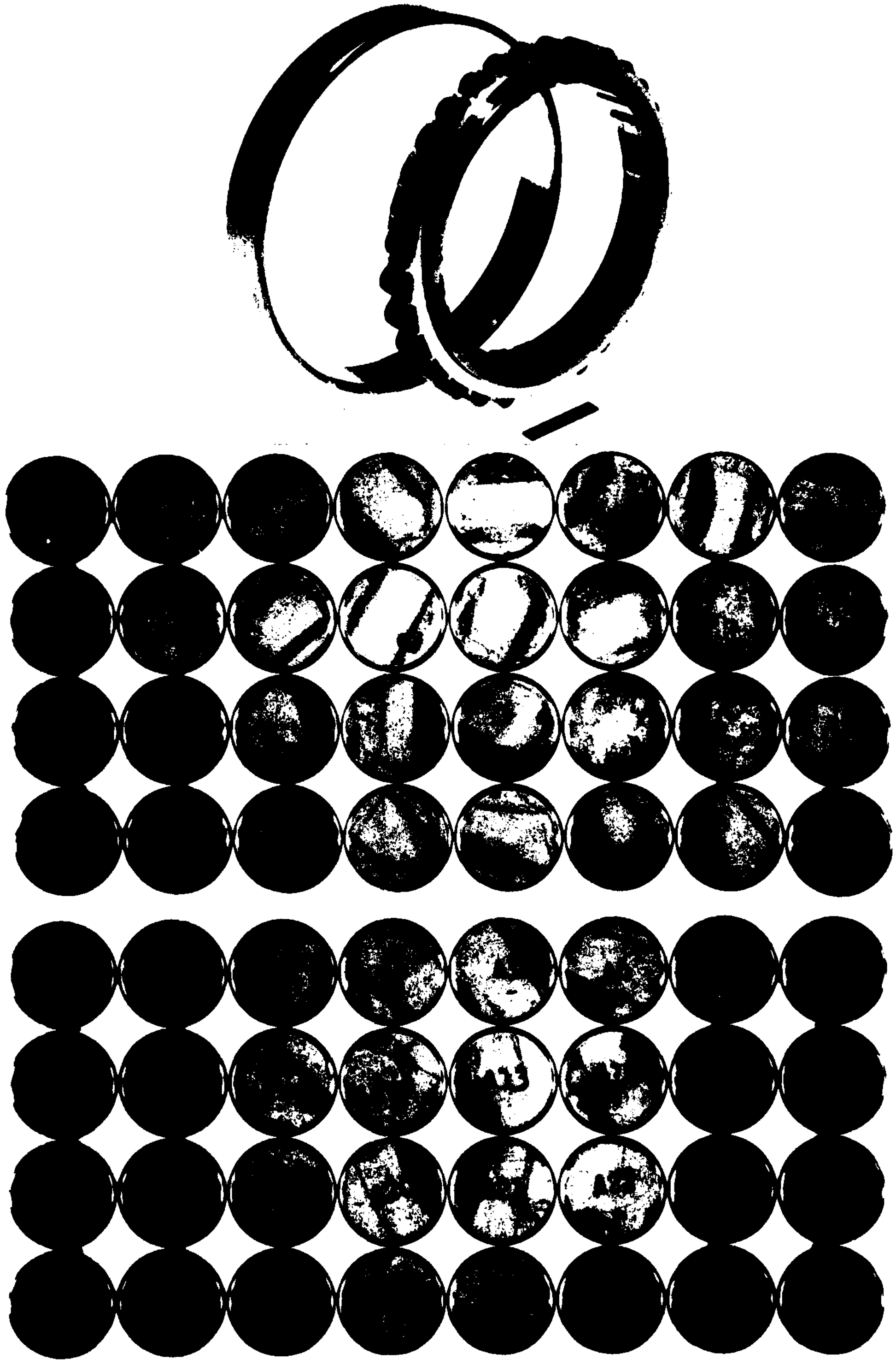

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Figure 10. Modified Bearing With Increased Unbalance (Test Bearing No. 1) Befor Eccentric End Wear Detection Test

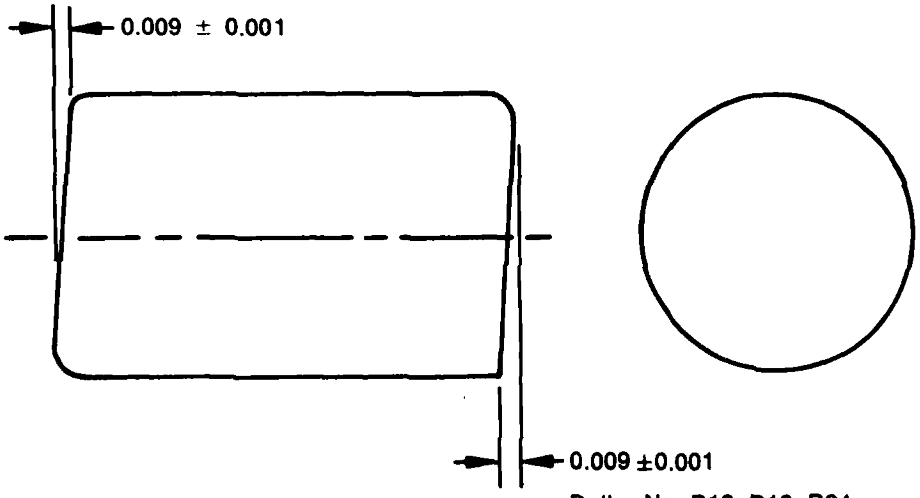

Figure 11. Modified Test Roller Bearing No. 2

Test Bearing No. 1 modifications and test conditions were designed to produce the moderate amount of roller wear debris which is associated with roller eccentric end wear.

The test conditions were formulated to provide an approximate one hour "run in" period in which the bearing would experience the normal break-in wear. This was followed by 9 hours of operation at conditions which were designed to produce the maximum test bearing wear possible. The test conditions included: elevated oil supply temperature, overspeed and radial loads adjusted to produce moderate cage slippage. The test conditions are summarized in Table 7.

TABLE 7. TEST SUMMARY TEST BEARING NO. 1

Point Number	Shaft Speed (rpm)	Load (Pounds)	Cage Speed (rpm)	Cage Speed (% Theoretical)	Oil Temp (°F)	Test Time	
						From	To
1	1,000	0	Not Measured	N/A	225	00:00	00:10
2	9,000	416	1,297	31	225	00:10	00:14
3	9,000	1,500	4,130	100	225	00:14	01:00
4	14,600	1.500	Not Measured	N/A	225	01:00	01:04
5	15,000	358	6,370	92.5	300	01:04	06:45
6	15,000	433	6,340	92.1	300	06:45	08:00
7	9,000	425	Not Measured	N/A	200	08:00	08:13
8	15,000	425	5,950	86.4	290	08:13	08:20
9	15,000	508	6,380	92.7	300	08:20	08:40
10	15,000	642	6,320	91.8	300	08:40	10:00

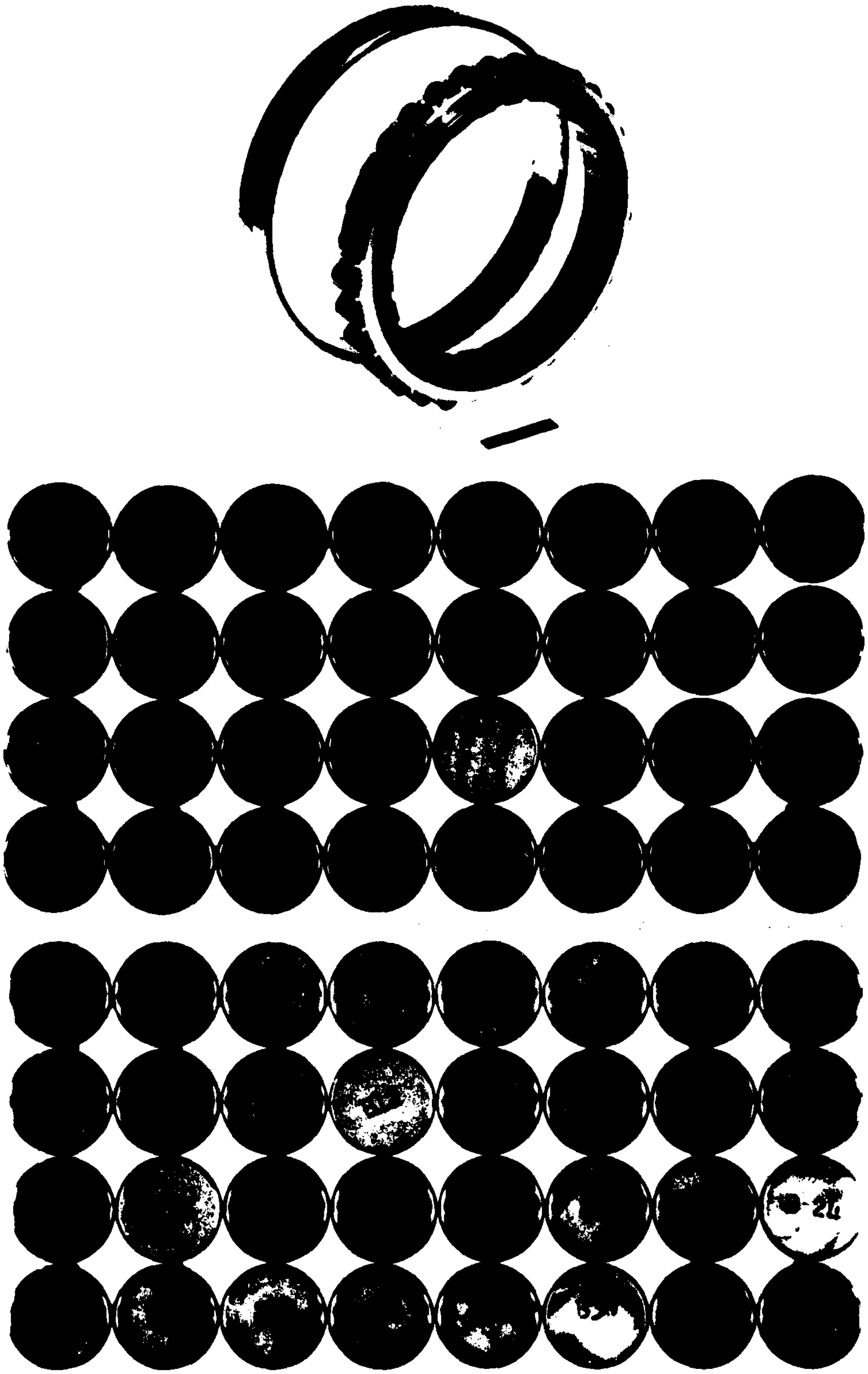

Figure 12. Modified Bearing With Increased End Run Out (Test Bearing No. 2)

Test Bearing No. 2 modifications were designed to produce the relatively large amounts of roller wear which results from the severe bearing distress caused by advanced eccentric end wear progressing to cage cross-rib fracture and roller to roller O.D. contact. The severity of the roller modification ensured cage fracture at speeds above 9000 rpm. The test conditions for bearing No. 2 were structured to avoid a premature test termination because of rig/bearing instability and to produce the maximum amount of roller wear over a ten hour test. These conditions included normal oil supply temperature, a gradual increase in rig speed and radial loads adjusted (in the early test stages) to the minimum amount at which the cage would not slip. The test conditions are summarized in Table 8.

TABLE 8. TEST SUMMARY TEST BEARING NO. 2

Point Number	*Shaft Speed (rpm)*	*Load (Pounds)*	*Cage Speed (rpm)*	*Cage Speed (% Theoretical)*	*Oil Temp (°F)*	*Test Time From*	*Test Time To*
1	558	416.7	240	93.7	221	00:00	01:04
2	1,028	166.7	520	110.2	221	01:04	02:03
3	1,993	166.7	910	99.5	223	02:03	03:05
4	3,063	516.7	1,400	99.6	227	03:05	04:03
5A	3,995	1,333.3	1,830	99.8	224	04:03	04:36
5B	3,981	311.7	1,690	92.5	224	04:36	05:15
6A	6,000	483.3	2,550	92.6	216	05:15	05:31
6B	6,000	433.3	1,613	58.6	223	05:31	05:46
6C	6,000	433.3	2,540	92.2	230	05:46	06:01
6D	6,000	416.6	3.160	114.7	226	06:01	06:16
7A	8,000	266.7	2,550	69.4	226	06:16	06:46
7B	8,000	325.0	3,410	92.9	225	06:46	07:06
8A	10,000	533.3	4,240	92.4	226	07:06	07:46
8B	10,000	583.3	2,060	44.9	226	07:46	09:31
8C	10,000	833.3	*	N/A	225	09:31	09:46
8D	10,000	1,500.0	*	N/A	224	09:46	10:01

*Internal Rig Cage Speed Instrumentation Damaged by Cage Debris

3. TEST RESULTS

A. Bearing Inspection

Pre- and post-test inspections of ***test bearing No. 1*** summarized in Table 9 and Figure 13 document the heavy roller end wear on the modified rollers, A12, A18, A24 and A30, as well as, the broken cage cross-rail associated with roller A30 cage pocket. All other cross rails associated with the deviated rollers exhibited cracks where the cross rails intersect the cage side rails.

While the bearing distress had proceeded to the point of cross rib fracture, the cross rib, at test completion, was still contained by the cage side rails and located between the two associated rollers, A30 and A31. This condition prohibited the high roller wear associated with roller to roller OD contact.

Test bearing No. 2 pre- and post-test inspections, summarized in Table 10 and Figure 14, document the roller wear and extensive cage distress. During the course of the test, twenty-three cage cross rails were broken.

Test bearing chip detectors began to indicate cross rail debris at 7 hours and 30 minutes endurance time (26 minutes after establishing 10,000 rpm shaft speed — test point 8A).

TABLE 9. TEST BEARING NO. 1 INSPECTION DATA

	Pre-Test	Post-Test	Δ
Roller Weights	A12 — 24.5795 Grams	24.5503 Grams	−0.0292 Grams
	A18 — 24.5416 Grams	24.5106 Grams	−0.0310 Grams
	A24 — 24.5615 Grams	24.4933 Grams	−0.0682 Grams
	A30 — 24.5865 Grams	24.5519 Grams	−0.0346 Grams
	Total Roller Weight Loss		0.163 Grams
Roller Diameter			
	Average 0.62997 ± 0.00002 in.	A29 - 0.62995 in.	—
		A30 - 0.62983[1] in.	−0.00014 in.
		A31 - 0.62998 in.	—
		A32 - 0.62995 in.	—

	Post-Test			
	Serialized End		Plain End	
	Maximum	Minimum	Maximum	Minimum
Roller Eccentric End Wear[2]	A5 - 0.0238	0.0238	0.0206	0.0206
	A12 - 0.0695	0.0291	0.0696	0.0284
	A17 - 0.0250	0.0250	0.0235	0.0235
	A18 - 0.0673	0.0292	0.0718	0.0282
	A24 - 0.0927	0.0436	0.0988	0.0378
	A30 - 0.0704	0.0320	0.0622	0.0258

o Roller No.'s A12, A18, A24 and A30 are modified rollers. (Figure 9)

o Rollers No.'s A5 and A17 represent typical unmodified rollers.

(1) The cage experienced a cross rail fracture between roller No.'s A30 and A31

(2) Roller eccentric end wear is a measurement of the maximum and minimum values of the roller end wear band. (Figure 6)

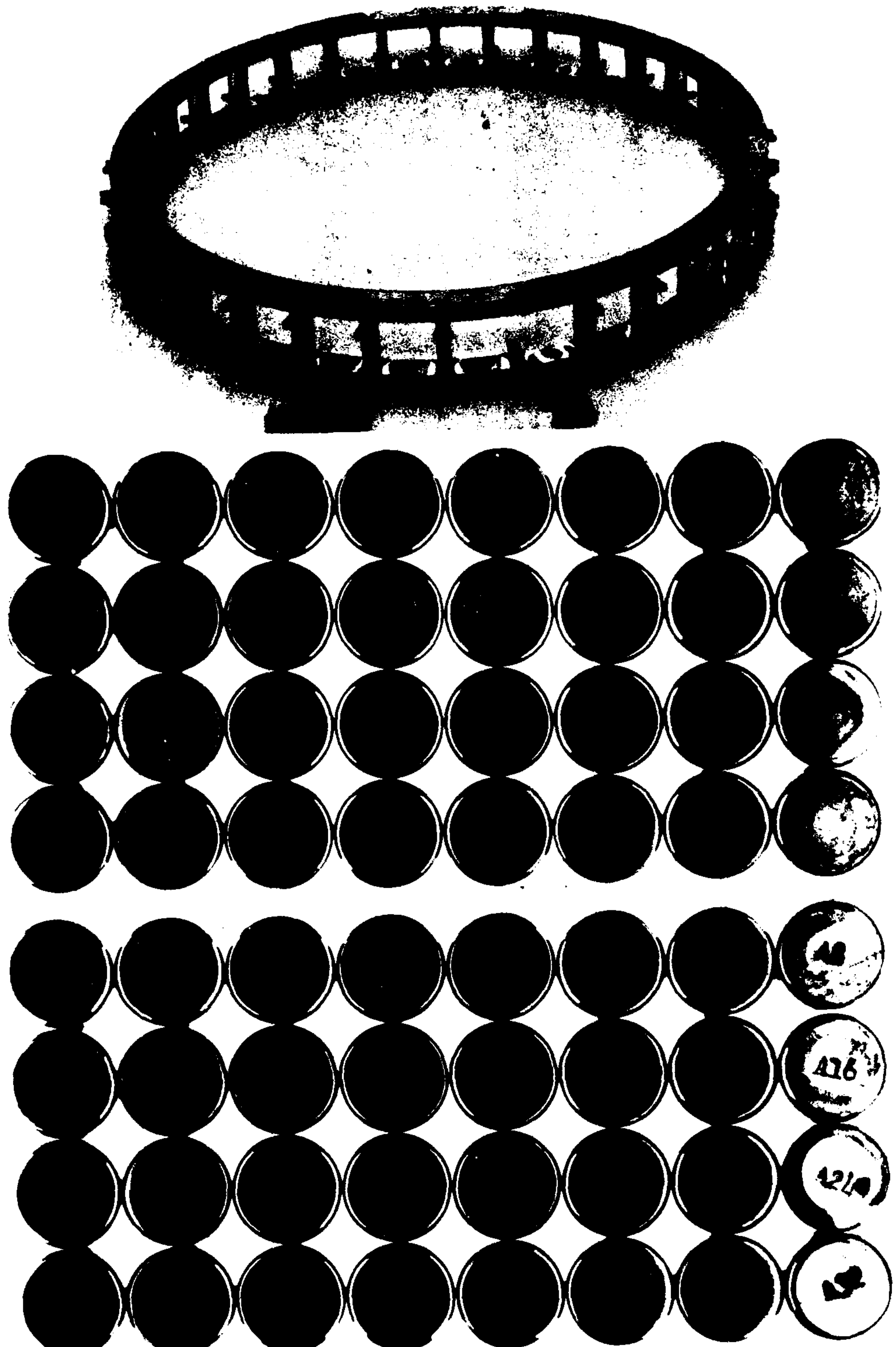

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Figure 13. Modified Bearing With Increased Unbalance (Test Bearing No. 1) After Eccentric End Wear Detection Test

TABLE 10. TEST BEARING NO. 2 INSPECTION DATA

		Pre-Test	*Post-Test*	Δ
Roller Weights	B1	— 24.7261 Grams	24.7249 Grams	−0.0012 Grams
	B2	— 24.7435	24.7240	−0.0015
	B3	— 24.7135	24.7123	−0.0012
	B4	— 24.7427	24.7413	−0.0014
	B5	— 24.7406	24.7393	−0.0013
	B6	— 24.7477	24.7468	−0.0009
	B7	— 24.7457	24.7448	−0.0009
	B8	— 24.7529	24.7519	−0.0010
	B9	— 24.7136	24.7087	−0.0049
	B10	— 24.7095	24.6999	−0.0096
	B11	— 24.7604	24.7362	−0.0242
	B12*	— 24.4917	24.2080	−0.2837
	B13	— 24.7117	24.5076	−0.2041
	B14	— 24.7242	24.6990	−0.0252
	B15	— 24.7124	24.6905	−0.0219
	B16	— 24.7289	24.7054	−0.0235
	B17	— 24.7126	24.6804	−0.0322
	B18*	— 24.4924	24.0535	−0.4389
	B19	— 24.7239	24.2789	−0.4450
	B20	— 24.7233	24.5108	−0.2125
	B21	— 24.7268	24.6939	−0.0329
	B22	— 24.7131	24.6752	−0.0379
	B23	— 24.7339	24.7042	−0.0297
	B24*	— 24.4376	24.3635	−0.0741
	B25	— 24.7228	24.6856	−0.0372
	B26	— 24.7182	24.6981	−0.0201
	B27	— 24.7508	24.7496	−0.0012
	B28	— 24.7282	24.7242	−0.0040
	B29	— 24.7305	24.7216	−0.0089
	B30*	— 24.4624	24.4090	−0.0534
	B31	— 24.7355	24.7130	−0.0225
	B32	— 24.7373	24.7183	−0.0190
			Total Roller Weight Loss	−2.0741 Grams
Roller Diameter		0.62972 Average ±0.00002	B12* 0.62867	−0.00105
			B13 0.62870	−0.00102
			B18* 0.62710	−0.00262
			B19 0.62500	−0.00472
			B20 0.62715	−0.00257
			B24* 0.62973	—
			B30* 0.62973	—

		Post-Test			
		Serialized End		*Plain End*	
		Maximum	*Minimum*	*Maximum*	*Minimum*
Roller Eccentric End Wear[1]	B5**	0.0158	0.0158	0.0250	0.0250
	B12*	0.0805	0.0275	0.0615	0.0224
	B13	0.0224	0.0224	0.0265	0.0265
	B18*	0.0862	0.0418	0.0740	0.0460
	B19	0.0494	0.0494	0.0467	0.0467
	B20	0.0262	0.0262	0.0290	0.0290
	B24*	0.0870	0.0374	0.0960	0.0245
	B30*	0.0918	0.0208	0.0652	0.0200

**Roller No. B5 represents a typical lightly worn roller

* Rollers No.'s B12, B18, B24 and B30 are modified rollers (Figure 11)

(1) Roller eccentric end wear is a measurement of the maximum and minimum values of the roller end wear band. (Figure 6)

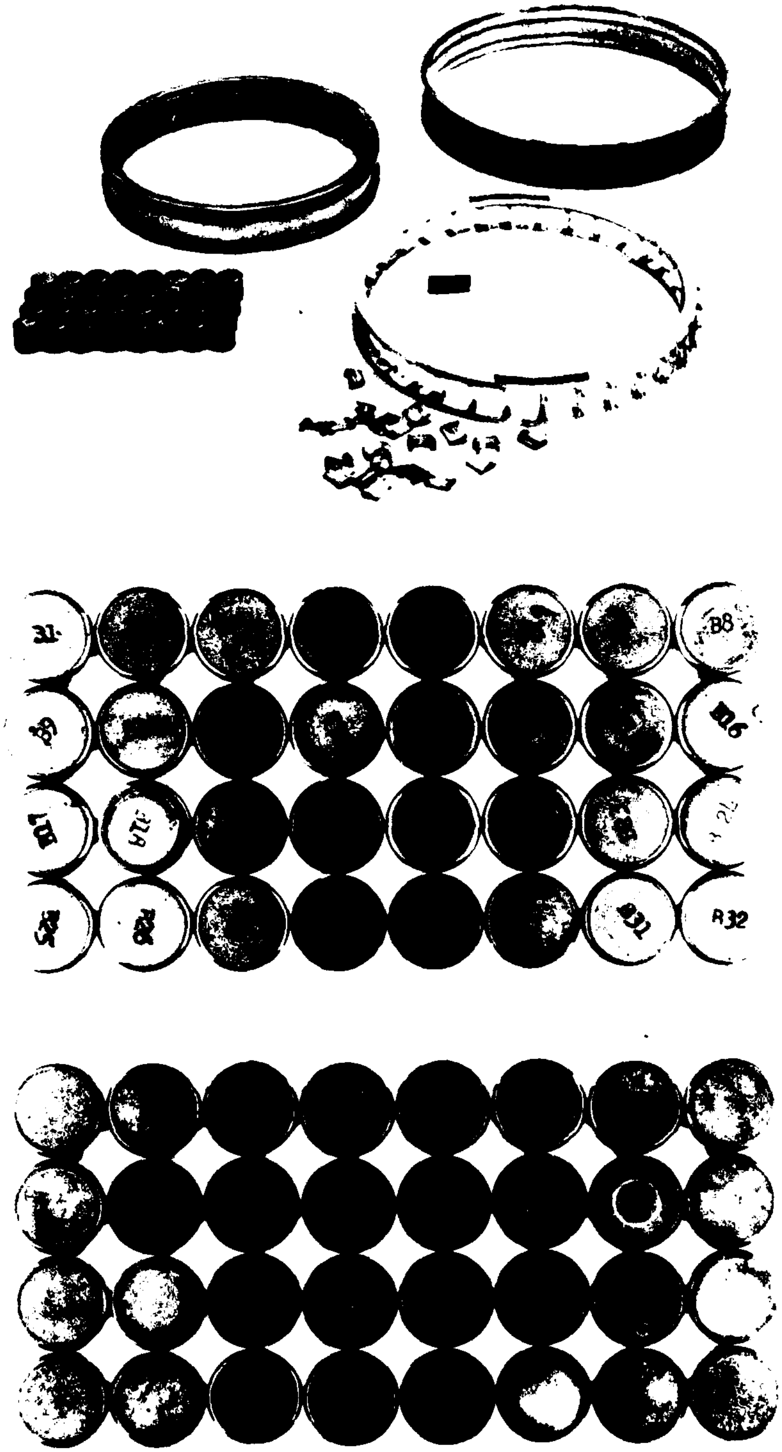

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Figure 14. Modified Bearing Rollers With Increased End Run Out (Test Bearing No. 2) After Cage Fracture Test

Roller diameter wear, the result of roller to roller OD contact, is particularly evident on test rollers B12, B13, B18, B19 and B20. Figure 15 contrasts the lightly worn roller surfaces of B27 with those of roller B18.

B. Oil Analysis Results

Prior to each test start-up and at 15 to 20 minute run-time intervals approximately 470 gm of oil were collected from the test bearing oil scavenge system (two 200-gm samples for radioactive debris analysis and one 70-gm sample for SOAP analysis). To maintain the 13-gal oil volume, clean make up oil was added after each oil sample was collected. The dilution effect of removing less than 1% of the total system debris per sample set is negligible with regard to the results obtained from both tests.

The oil samples were subjected to absorption and emission SOAP (spectrometric oil analysis program) procedures, and radiological evaluation (Section V). The results of these studies are plotted against one another for test bearings No. 1 and No. 2 in Figures 16 and 17 respectively. In each oil sample set the radiological tagging technique indicated that the irradiated rollers experienced a jump in wear at a point in time which agrees with all three conventional oil-borne iron detection techniques. In addition, the shape of the generated graphs, in each case, clearly indicates the distress mode and wear regime experienced by each bearing during the tests, as confirmed by post-test inspections.

Test Bearing No. 1 oil analysis results are detailed in Figure 16. The first hour indicates low roller wear and moderate overall iron debris generation (given the bearing modification). The ramp between 1 hour and 1 hour 15 minute represents the rapid progress of bearing wear, produced primarily by the combination of bearing modification and the rig acceleration to 15,000 rpm shaft speed. The flat portion of the graph is indicative of the following 5 hour and 25 minute steady-state rig operation.

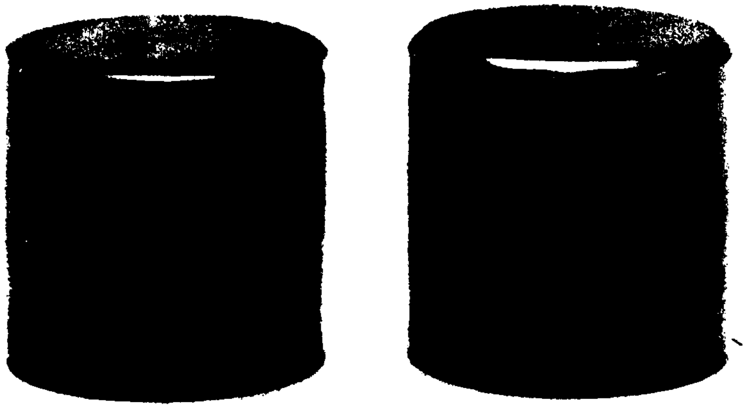

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Figure 15. Comparison of the Lightly Worn Roller Surfaces o Roller B27 With Those of Modified Roller B18

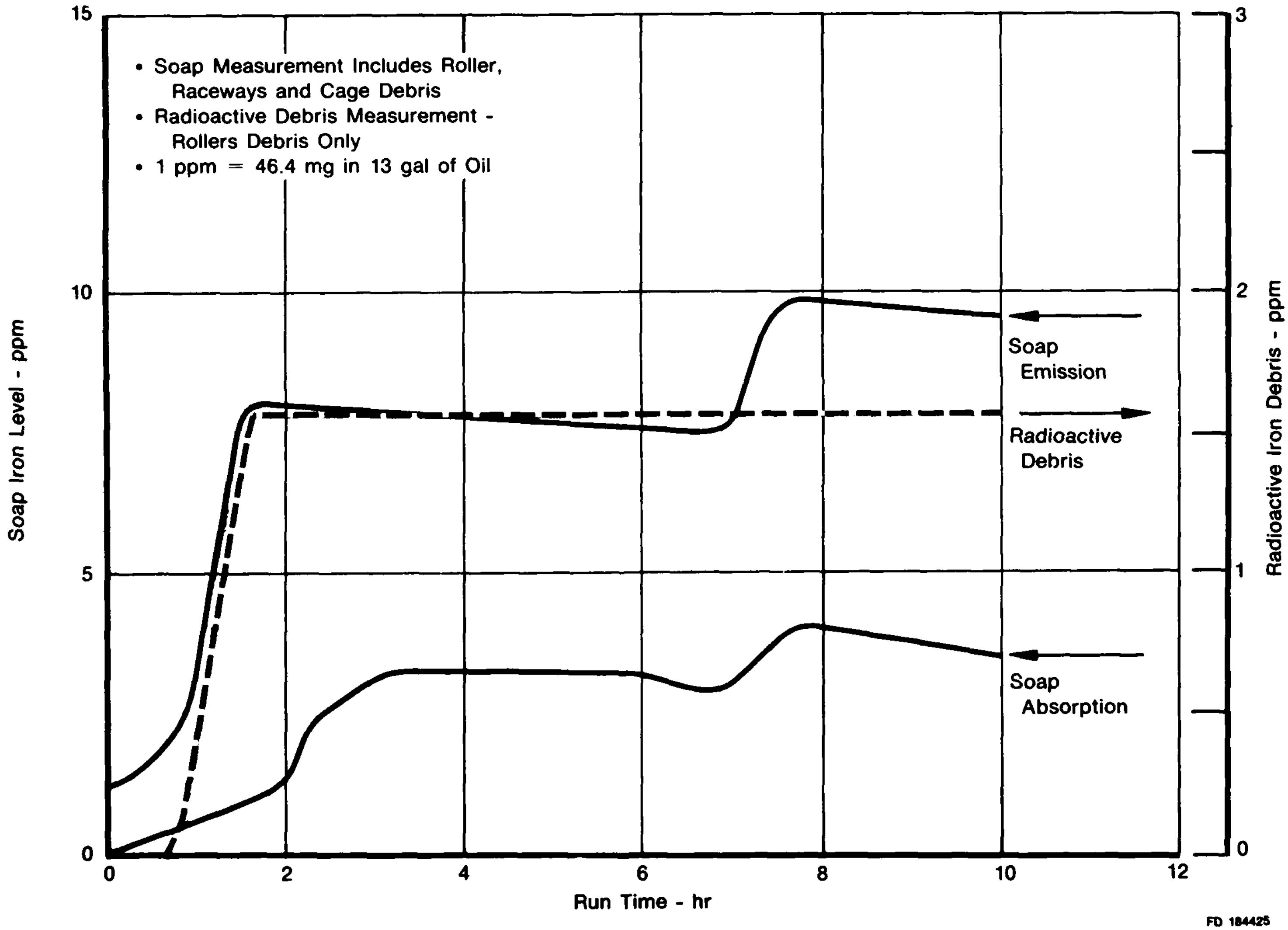

Figure 16. Test Bearing No. 1 Oil Analysis Results

A slave bearing lubrication supply line ruptured 6 hours and 40 minutes into the test program and resulted in an unscheduled rig shutdown. In the course of effecting system repairs, the oil tank was drained (10 gallons) and refilled (original 10 gal plus 3 gals make-up oil). The perturbation in SOAP data at that time is the result of a mixing action of settled test bearing cage debris. As expected, no change was evidenced in the radioactive measurement due to the low settling rate of the radioactive debris stemming from roller end wear.

Test Bearing No. 2 Oil Analysis results are detailed in Figure 17. The data indicate that test bearing wear initiated after 6 to 7 hours of testing (6000 rpm/416.6 lb load — 8000 rpm/325 lb load). The wear rate increased significantly after establishing the 10,000 rpm/533.3 lb load test conditions. Heavy roller wear (radiological measurements) and overall test bearing wear (SOAP) generation continued throughout the remaining 3 test hours.

4. TEST FACILITIES

A. Test Rig and Stand Drive System

The bearing test rig, Figure 18, used to test the No. 4 roller bearing consists of a cylindrical housing which contains the supporting structures for the shaft, an externally mounted pneumatic load cylinder, and a shaft/bearing assembly. A schematic diagram of the rig is shown in Figure 19.

Four bearings are located on a common shaft assembly in the rig. The shaft, supported at the front (drive) end by a slave bearing assembly consisting of a duplex ball bearing and a roller bearing, holds the test bearing at the mid-section and is supported at the rear by a single slave roller bearing. A picture of the shaft assembly is shown in Figure 20. The rear slave roller bearing may be loaded by a load cylinder which is radially guided by tracks in the housing. The radial load to the rear slave bearing is transmitted through the shaft assembly to both the test bearing and front slave bearing and through supporting structures to the rig housing. The axial location of the shaft assembly is controlled by the duplex ball bearing.

The rig is driven by a 350-hp Marathon variable speed electric dc motor having a maximum speed of 4500 rpm. The rig is coupled to the motor by a Western gear box with a 7.54 to 1 step-up. A 60-tooth gear is attached to the motor shaft, which is used in conjunction with a magnetic pick-up to determine rig shaft speed. Gear box vibration is monitored by accelerometers attached to the gear box in both the horizontal and vertical planes. The spline interconnecting and gear box and rig has a shear section to protect the gearbox, drive motor, and test rig in case of failure.

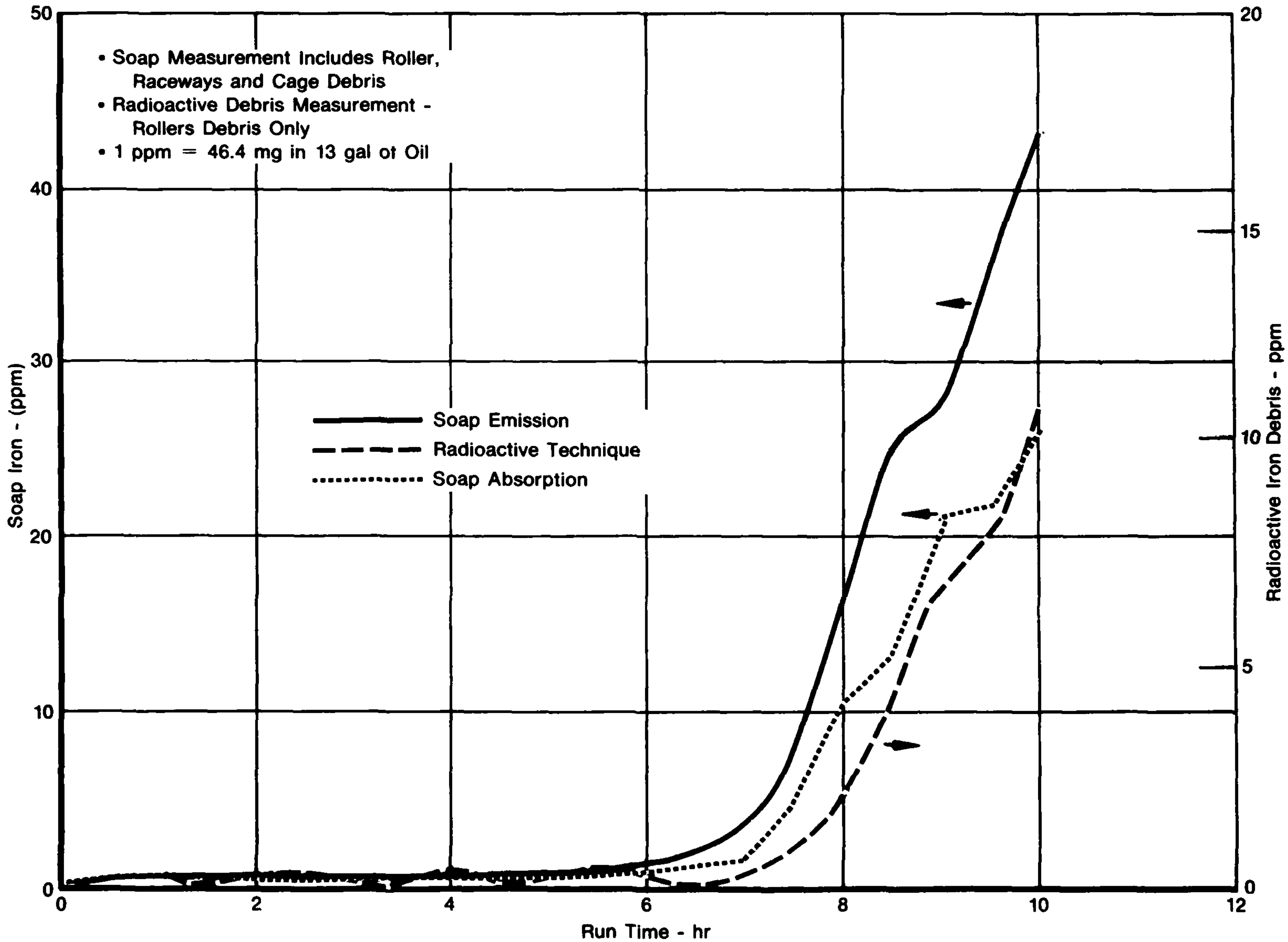

Figure 17. Test Bearing No. 2 Oil Analysis Results

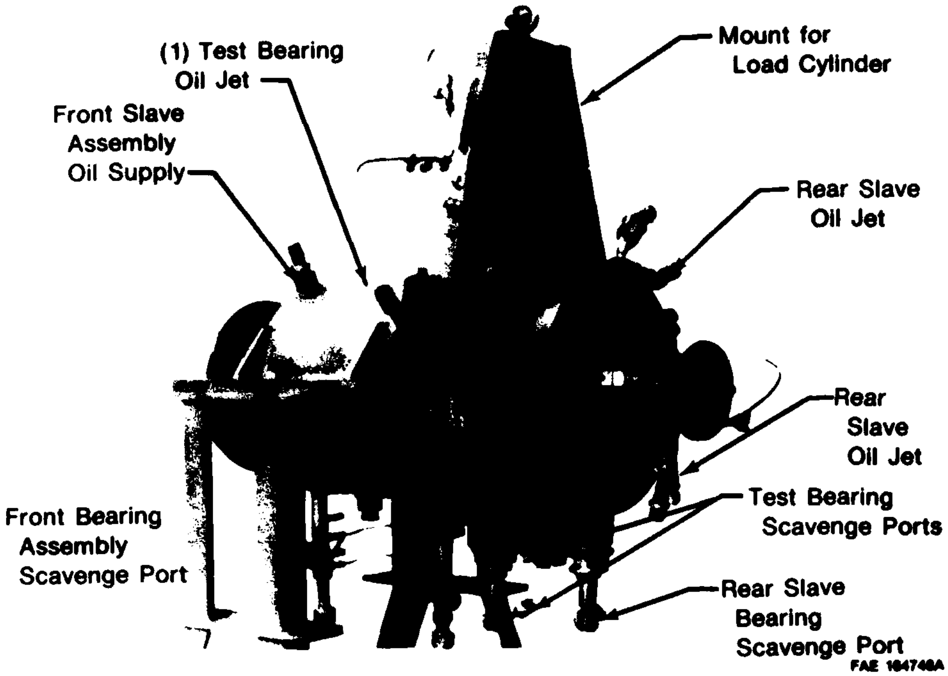

Figure 18. Test Rig

B. Lubrication System

Lubrication and cooling oil is supplied to the test bearing by directing oil into both sides of the bearing housing by means of fixed oil jets. The oil impinges on a radial scoop which channels oil to axial slots located on the bore of the rotating inner race. Four radial holes in the inner race intercept axial slots and direct oil to the inner race functional surfaces from which the oil flows to the rollers and outer race. The bulk of the oil supplied to the inner race axial slots, after extracting heat from the inner race bore, is passed on through radial holes in a nonfunctional seal plate.

The test rig is serviced by the lubrication system shown schematically in Figure 21. The system supplies, controls, and monitors the temperature, pressure, and flow of the oil used for lubrication and cooling of the test bearing and slave bearings.

The rig lubrication system includes an oil reservoir which supplies oil to a high capacity positive displacement pump. The oil flows from the pump to a high capacity heat exchanger and into an oil supply manifold. The oil flow to the test and slave bearings is controlled by a parallel system of three pneumatic control valves. The by-pass valve shunts excess oil from the pump discharge back to the oil reservoir. Two additional valves are used to control the flow split between the test and slave bearings. Oil destined for the test bearing then traverses successively through a heat exchanger, a filter (70μ), turbine flow meter, and a second filter (70μ). Downstream of the filter, the flow splits equally to the two test bearing jets. The test bearing scavenge system consists of three separate legs. Each flowpath has its own magnetic chip detector to assess bearing distress, as well as a positive displacement pump which returns the oil back to the reservoir. A similar lubrication system exists for the slave bearings.

The lubricant selected for this program is a synthetic oil which conforms to MIL-L-7808G specifications.

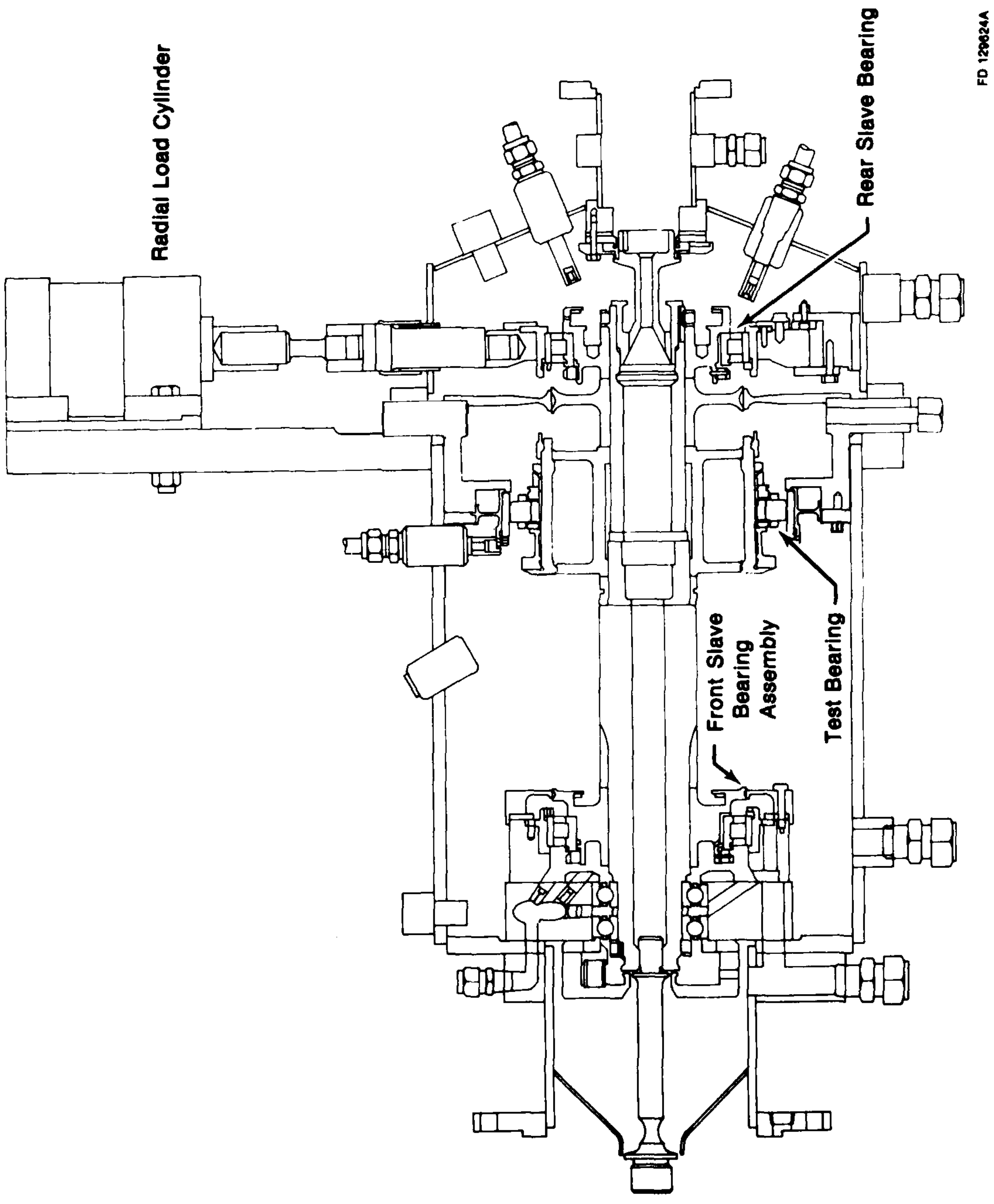

Figure 19. Test Rig Schematic

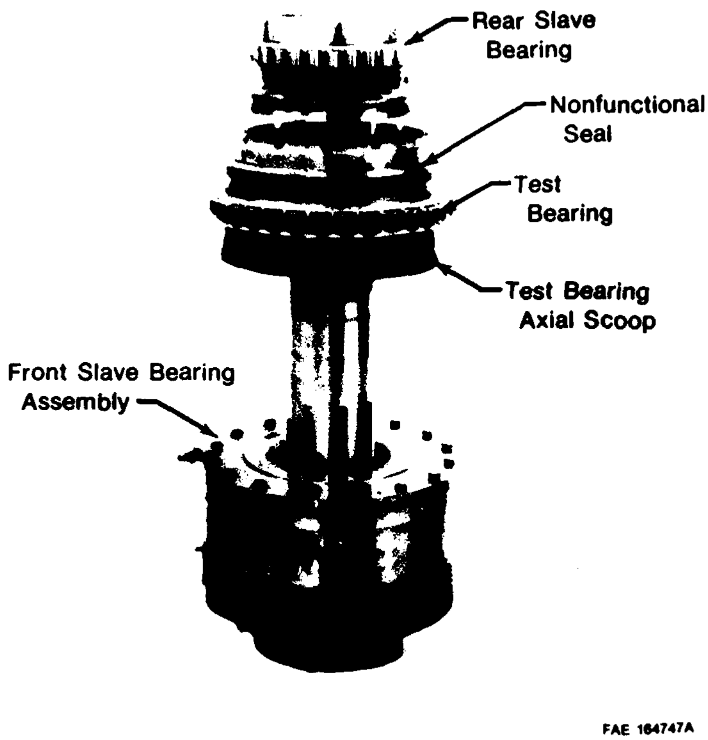

Figure 20. Bearing/Shaft Assembly for Test Rig

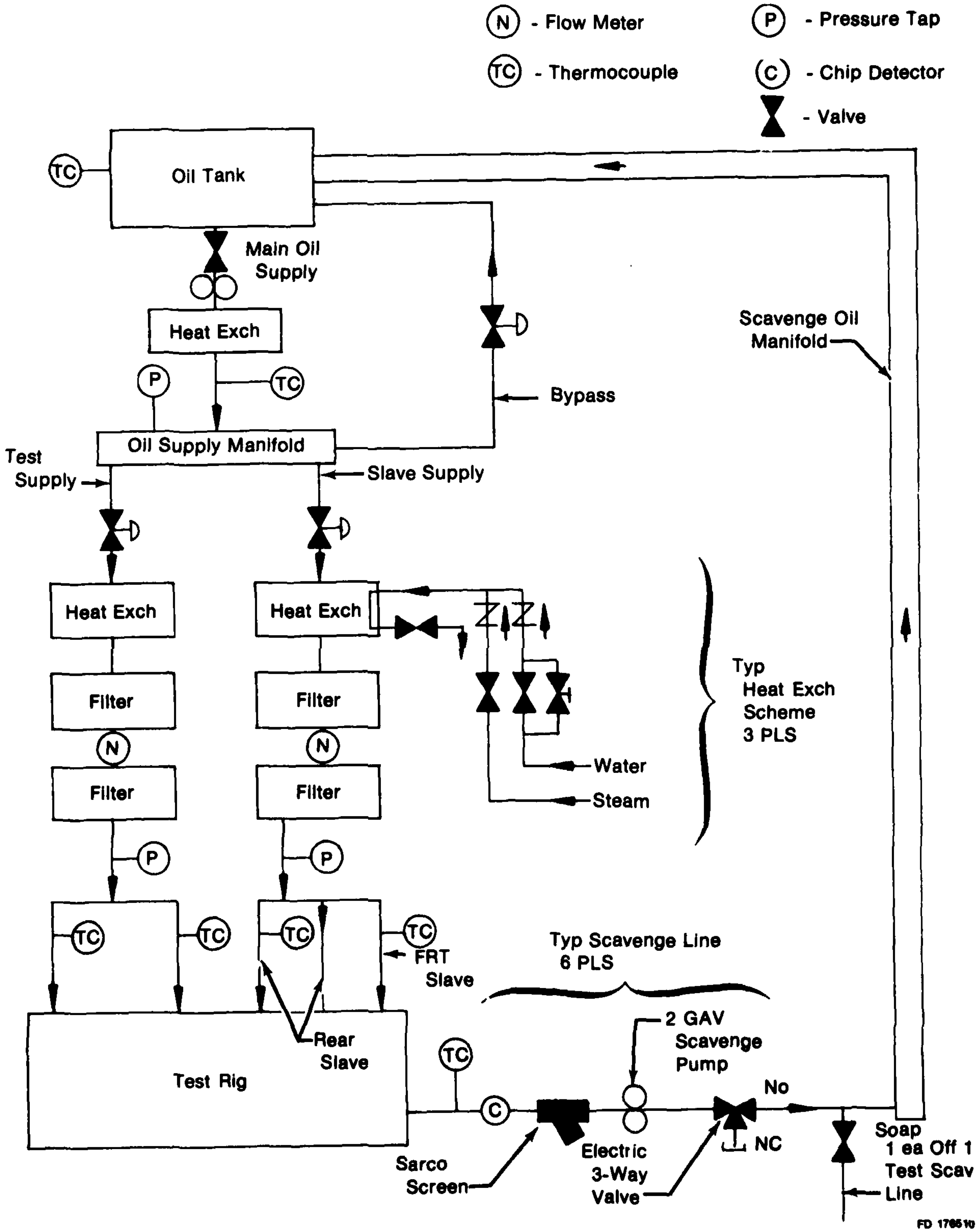

Figure 21. Test Rig Lubrication System

C. Instrumentation

Instrumentation is provided to measure the imposed test conditions, the bearing operating conditions and the operating conditions of the test rig. Table 11 lists the measurements obtained and identifies the corresponding type of instrumentation employed. Manual recording of all measurements were made every 15 minutes during the test program.

TABLE 11. TEST INSTRUMENTATION

Measurement	Instrumentation
A. *Imposed Test Conditions*	
Rig Shaft Speed	Magnetic pickup with direct digital readout
Applied Radial Load	Pressure tap at pneumatic load cylinder supply port, with pressure gage readout
Oil Flow to Test Bearing	1. Turbine type oil flowmeter with direct digital readout, installed in oil supply lines 2. Pressure tap in oil supply line with pressure gage readout
Oil Supply Temperature to Test Bearing	Chromel-Alumel thermocouples installed in oil supply lines with direct digital readout
B. *Test Bearing Operating Conditions*	
Outer Race Temperature	Chromel-Alumel thermocouples installed in housing contacting bearing outer race, with direct digital readout
Discharge Oil Temperature	Chromel-Alumel thermocouples installed in discharge oil rig sumps
Vibrations	Accelerometers mounted in the vertical and horizontal planes on the test bearing outer race support with a vibration displacement meter readout
Cage Speed	Proximity probe addressing scribed marks on the test bearing cage with an oscilloscope display and digital readout
C. *Rig Operating Conditions*	
Oil Supply Temperature to Slave Bearings	Chromel-Alumel thermocouples installed in oil supply lines with direct digital readout
Slave Bearing Oil Discharge Temperatures	Chromel-Alumel thermocouples installed in discharge oil rig sumps with direct digital readout
Oil Flow to Rig	1. Turbine type flowmeter with direct digital readout installed in oil supply line 2. Pressure tap in oil supply line with pressure gage readout
Slave Bearing Vibrations	Accelerometers mounted in the vertical plane on slave bearing outer race supports with vibration displacement meter readout

SECTION IV

DEBRIS RECOVERY

1. GENERAL

The radioactive bearing tagging technique requires separating the wear metal debris from the lubricating fluid. The specific amount of engine oil processed for wear metal debris recovery is dependent upon the required part per million threshold level for detection, the initial level of radioactivity concentration on the tagged roller, the nuclear debris counting system sensitivity, and the radioactive decay time.

Severe roller eccentric end wear from a typical high-speed application represents a mass loss of 9 to 15 mg. In a 5-gal oil system, typical of current jet engines, the lower mass loss is equivalent to 0.5 ppm. To provide detectability at the 9-mg eccentric end wear level, a 0.5 ppm debris detection threshold level will be used.

The oil sample volume required to achieve 0.5 ppm threshold detection as a function of radioactive decay is shown in Figure 22.

2. INITIAL EVALUATION OF WEAR METAL DEBRIS RECOVERY TECHNIQUES

A. General

An initial evaluation to determine the most practical method of wear metal debris recovery considered procedures such as filtration, centrifuging, and magnetic and solvent extraction. Centrifuging and solvent extraction were rejected because of the limited quantities

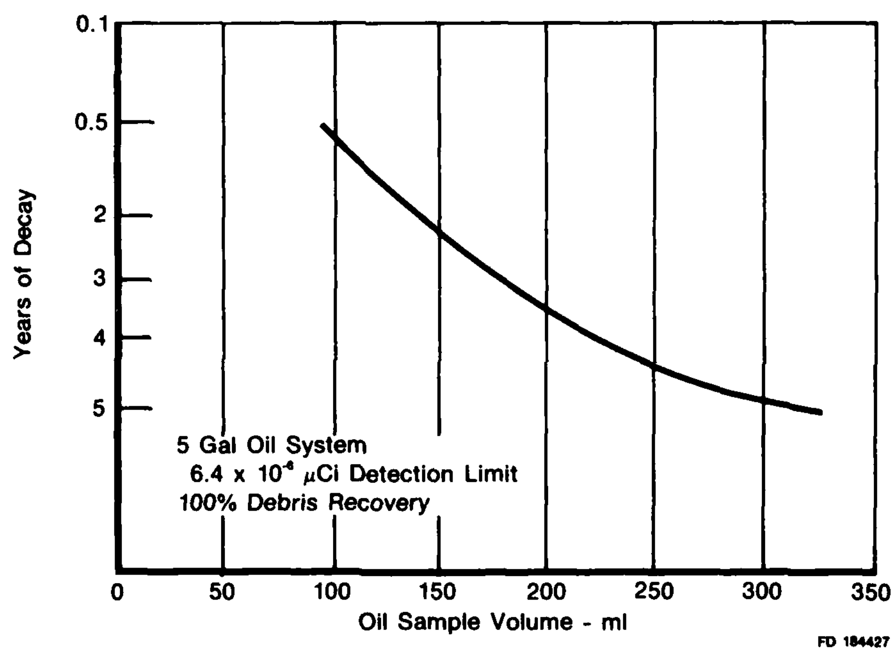

Figure 22. Oil Sample Volume to Achieve Required 0.5 ppm Debris Measurement Sensitivity

of oil that could be processed, and the complexities involved in processing the oil. Magnetic separation was found to be applicable to gallon-size oil samples, but filtration was determined to offer the most practical method of debris recovery. Thus, of all the various debris removal techniques examined, an optimal design appears to consist of either a vacuum or pressure filtration system incorporating a supported membrane filter (Reference 15).

The method used to obtain an oil sample for radioactive debris analysis must ensure that the sample represents the equilibrium wear metal concentrations existent during the operation of the engine oil system (Reference 16). Details regarding proper oil sampling methods are presented in the wear particles atlas (Reference 17). For the tagging system discussed in the following paragraphs, the SOAP oil removal techniques used in current engine oil systems are recommended.

B. Filtration

(1) Types of Filtration

Filtration media fall into two basic categories: "depth" and "membrane." Depth filters derive their name from filtration that occurs within the depth of the filter matrix. Filters of this type consist of a random matrix of fibers bonded together to form a complex maze of flow channels. Screen filters retain particles on their surfaces by physically screening them from the oil. The screen structure is normally rigid, uniform, and continuous; it is referred to as a membrane filter.

For recovery of wear metal debris from an engine oil system, a depth filter would entrap particles within the filter matrix and permit processing of gallon-size oil samples. However, the debris would be difficult to remove from the filter matrix for subsequent nuclear counting. A membrane filter is limited in the total volume of oil that can be filtered in a finite period. However, the membrane would position the wear debris on the filter surface which could then be directly introduced into the nuclear counting system.

(2) Engine Oil Membrane Filtration

The field application of the tagged main shaft bearing approach for incipient failure detection necessitates utilization of the least complicated method for removal of the wear metal debris from the engine oil. Due to its high capture efficiency and simplicity of use, membrane filtration has been chosen for wear particle removal. Membrane filtration using a 47-mm pressure holder (Millipore Corporation type XX40 047 40) was selected for laboratory testing (Figure 23).

(3) Membrane Filtration of the Various MIL-L-7808 Formulations

In order to determine the applicability of membrane filtration to various manufacturer lubricant formulations of MIL-L-7808, samples of Humble, Stauffer, Royal and Mobil were obtained. Fifty-gram samples were heated to 150°F, poured into a 47-mm pressure holder and pressurized to 10 psig with nitrogen. Initial testing using 1μ Millipore Fluoropore (polytetrafluoroethylene bonded to a polyethylene net) showed the Stauffer lubricant was not filterable using a Millipore Fluoropore filter. Polycarbonate Nuclepore membrane 0.8μ filter showed compatibility with all manufacturer formulations, Table 12.

To provide additional information, 100-g samples of each of the oil types were also filtered using a 0.8μ Nuclepore filter under the same conditions. The Humble and Mobil lubricants required 20 and 40 sec, respectively. The Stauffer lubricant required 68 sec. Roughly 60% of the Royal lubricant passed through the filter in about 50 sec, after which the flow subsided to a slow drip.

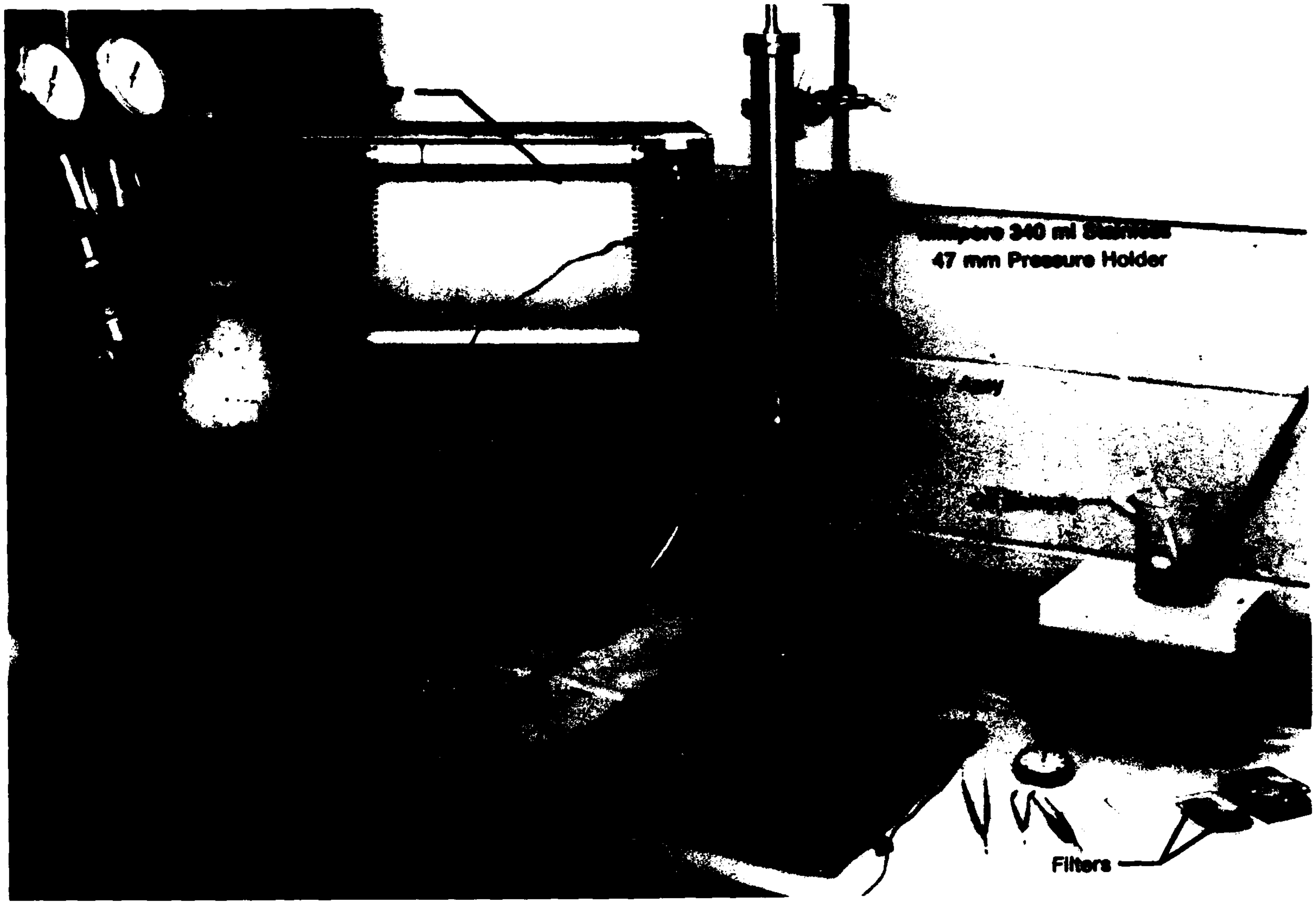

Figure 23. Membrane Filtration System for Wear Metal Debris Removal

TABLE 12. FILTRATION TIMES FOR VARIOUS OIL FORMULATIONS

Manufacturer	Formulation	Lot	Time (sec)[1][2]
Humble	1M1	31	15
Stauffer	18E1	7	22
Royal	3C3	23	26
Mobil	15D1	55	13

[1]Nuclepore filters 0.8μ
[2]50 gram oil sample.

Further testing using Millipore Fluoropore 0.5 and 1.0μ filters showed that for the Mobil and Humble lubricants filtration required about two to three times longer than was necessary using the Nuclepore filters. In a 100-g test, about 60% of the Royal lubricant passed through the filter in 95 sec before the flow stopped.

Although Nuclepore filters are compatible with the four formulations of MIL-L-7808 tested, Table 12, gasket sealing difficulties were encountered in using the Nuclepore filters in the 47-mm Millipore pressure holders. A redesign of the pressure holder would be required to provide the proper sealing surfaces. Nuclepore filters have the additional complication of containing picocures amounts of radioactivity. This then requires counting the filter before usage to establish background counts. To avoid both a pressure filter holder redesign and the requirement for precounting the filter, the Millipore Fluoropore filter will be used to process the test bearing rig lubricant samples (Exxon turbo oil) for debris concentration.

C. High Gradient Magnetic Separation

In order to minimize the initial radioactivity levels of the bearing material, it is advantageous to process as much of the engine oil as possible for recovery of the tagged wear metal debris. Magnetic separation has demonstrated capability of removing virtually all of the ferromagnetic wear particles in oil (Reference 18). The oil is pumped at a flowrate of 1 to 3 gal/min through a filter canister containing a stainless steel wool matrix. The canister, about the size of an automobile oil filter, is enclosed in an electromagnet capable of generating a magnetic field of 2 kilogauss. The coarse steel wool matrix induces large perturbations in the magnetic field intensity, thereby producing sharp magnetic gradients for trapping the wear debris onto the steel wool.

Removal of the debris from the steel wool matrix would be achieved by circulating an oil solvent through the canister with the power removed from the electromagnet. A membrane-type filter would then be used to remove the debris from the solvent. Discussions with magnetic separator manufacturers indicate that laboratory systems would cost upwards of $8,000, depending on the technical sophistication and system size. The system would, however, be bulky and would not lend itself to flight line usage. Due to the complications that arise from magnetic separation, this system has been discarded in favor of membrane filtration.

3. RADIOACTIVE WEAR METAL DEBRIS RECOVERY OF TEST BEARINGS

A set of two 200 gram oil samples was obtained every 15 or 20 min (depending on test bearing) during the rig testing for radioactive wear metal debris analysis. One oil sample from each set, approximately 200 grams, was processed for debris recovery. Each oil sample was weighed and then heated to between 140 to 175°F prior to introducing the sample into the 340 ml capacity barrel of the Millipore XX 40 47 mm pressure filter holder. Millipore Fluoropore 0.5μ membrane filters were used to recover the wear metal debris. Nitrogen pressure ranging

from an initial 20 psig to a final 65 psig was used. Approximately 5 min was required to filter the 200-gram oil samples.

In order to determine the presence of radioactive wear metal debris not removed by the 0.5μ Millipore Fluoropore filter, eight samples were refiltered using 0.1μ Nuclepore membrane filters. Nuclear counting indicated no radioactivity above the background level present on the 0.1μ filters. The second oil sample obtained at the 1 hr and 20 min testing time was first filtered through a 1μ Millipore filter and then filtered with a 0.1μ Nuclepore filter. The 1μ filter contained 1.6 ppm radioactive bearing debris; no radioactivity was indicated on the 0.1μ filter. (Refer to Section V.)

4. CONCLUSION

The radioactive bearing tagging technique requires the separation of the radioactive wear metal debris from the lubricating fluid.

Of the separation methods considered, membrane filtration was considered the most acceptable. Membrane filtration systems, in addition to being inexpensive and uncomplicated, have the distinct advantage of depositing the wear metal debris directly on the filter surface. This permits the direct incorporation of such debris into a nuclear counting system.

The low level radioactive roller debris is filtered out of the oil using membrane filtration in the 0.5 to 1.0μ range. The rig tests simulating turbine engine bearing operating conditions, conducted as a part of this program, indicate that, for the given bearing wear modes, the generated roller wear debris was 1.0μ or larger.

The specific amount of oil removed from a given system is dependent upon initial tracer activity, debris recovery efficiency, decay time, and the part per million threshold level required for detection.

SECTION V

NUCLEAR MEASUREMENTS OF RECOVERED WEAR METAL DEBRIS

1. RADIOACTIVE DEBRIS DETECTION

The amount of induced bearing roller radioactivity required to provide wear metal debris identification is directly dependent upon the lower limit detection accuracy of available nuclear counting instrumentation. This limit is a function of both instrument sensitivity to extraneous background counts and its efficiency in the detection of radiation emitted by the tagged debris.

Low-level wear debris sample measurements involve the use of techniques that minimize extraneous background. Background counts are principally attributed to environmental radioactivity, cosmic rays, and electronic "noise." Surrounding the detector assembly with lead shielding reduces the effects of environmental radioactivity. The positioning of a cosmic ray detector around the sample measuring detector provides a means of distinguishing cosmic ray counts from counts of radioactive debris. The use of anticoincidence circuitry will temporarily block instrument response to a cosmic ray event. The instrument will then register only the sample detector counts.

The low-energy 5.9 keV X-ray emissions from Iron-55 and the 695 keV Beta emissions from Krypton-85 require the selection of a radiation detection method which will provide maximum detectability. Scintillation counting experiences detectability limitations for these emissions, while gas proportional counting permits high detection (Reference 19). This greater detectability is critical in obtaining efficient counting sensitivity and background suppression. Gas proportional counters are between 5 and 10% efficient for the 5.9 keV X-ray and about 50% efficient for the 695 keV Beta ray.

2. GAS FLOW PROPORTIONAL COUNTING

The proportional counter is an ionization chamber type radiation detection device. Radiation is detected by the ionization of the contained argon gas either by collision with Beta particles, or through reactions with X-rays (Figure 24). Within the proportional counter the original electrons released by a nuclear event are multiplied by cascade ionization. This cascade ionization results from the electrical field acceleration force produced by a positively charged anode wire. The negative ions that are formed are attracted to the anode wire, while the positive ions are attracted to the cathode housing. The excessive charge on the anode wire is removed by the high voltage supply, resulting in a fast pulse of current through the anode wire. This fast charge pulse is electronically processed to a proportional voltage pulse. Each processed voltage pulse over a set voltage range represents a nuclear event, or count.

Both a Nuclear Measurement Corporation PCC-11TC and a Canberra Industries 2200 flow proportional counter were used in this program. The NMC is a windowless proportional counter; the sample is positioned within the counter, Figure 25, which is itself enclosed by 0.5-in. lead shield. The Canberra sample counter has a 0.02 mil mylar window (99.9% transparent to the Iron-55 5.9 keV X-rays). The Canberra unit has a sealed cosmic ray detector located above the sample counter, Figure 26, and both detectors are enclosed in 4 in. of lead lined with 0.25 in. copper. Although the background sensitivity of the Canberra unit is 34 times lower than that of the NMC unit, the former's efficiency for detecting the 5.9 keV X-rays from Iron-55 is only 42% that of the NMC. The lower Iron-55 sensitivity is attributed to the $\approx$ 2.5 cm path length in the NMC vs the $\approx$ 1.0 cm path length of the Canberra. The counting statistics for the lowest level of debris detection for both units is given in Table 13.

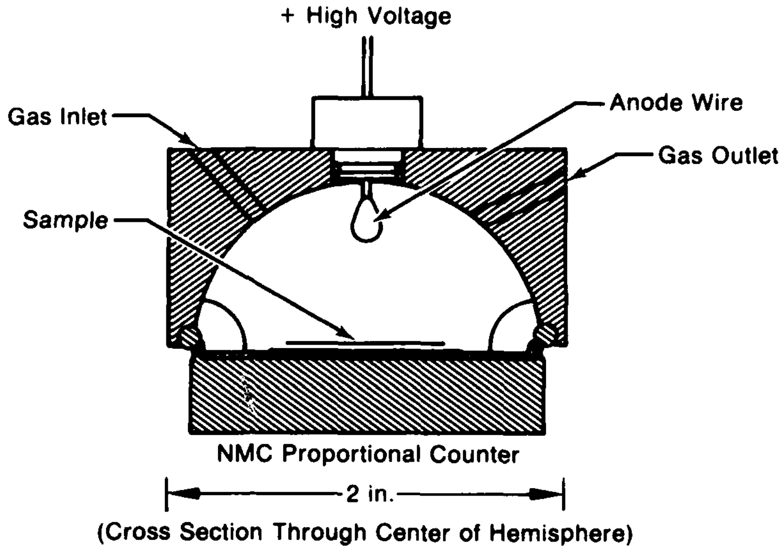

Figure 24. Proportional Counter Ionization Chamber

TABLE 13. COUNTING STATISTICS FOR THE LOWER LEVEL OF DEBRIS DETECTION

Ambient Background (Counts/Min)	*Two-Sigma[3] Standard Deviation (Counts/Min)*		*Minimum Level of Detection (pCi)[4][5]*			
	50 Min Counting Time	200 Min Counting Time	50 Min Counting Time		200 Min Counting Time	
			Iron-55	Krypton-85	Iron-55	Krypton-85
30[1]	2.2	1.1	31.2	1.59	15.6	.9
0.88[2]	0.38	0.187	13.0	0.40	6.40	0.20

(1) Nuclear Measurement Corporation (PCC-11TC)

(2) Canberra Industries (2200)

(3) Two Sigma Standard Deviation = 2 $\sqrt{\text{2X Background Counts}}$

(4) pCi = 10^{-12} Curies = 10^{-6} microcuries = 2.22 disintegration per minute

(5) Conversion from CPM to microcuries using the following detector efficiencies and emission fraction.

	Detector Efficiencies		*Emission Fraction*
	NMC	Canberra	
Iron-55	0.11	0.047	0.28
Krypton-85	0.6	0.43	1.0

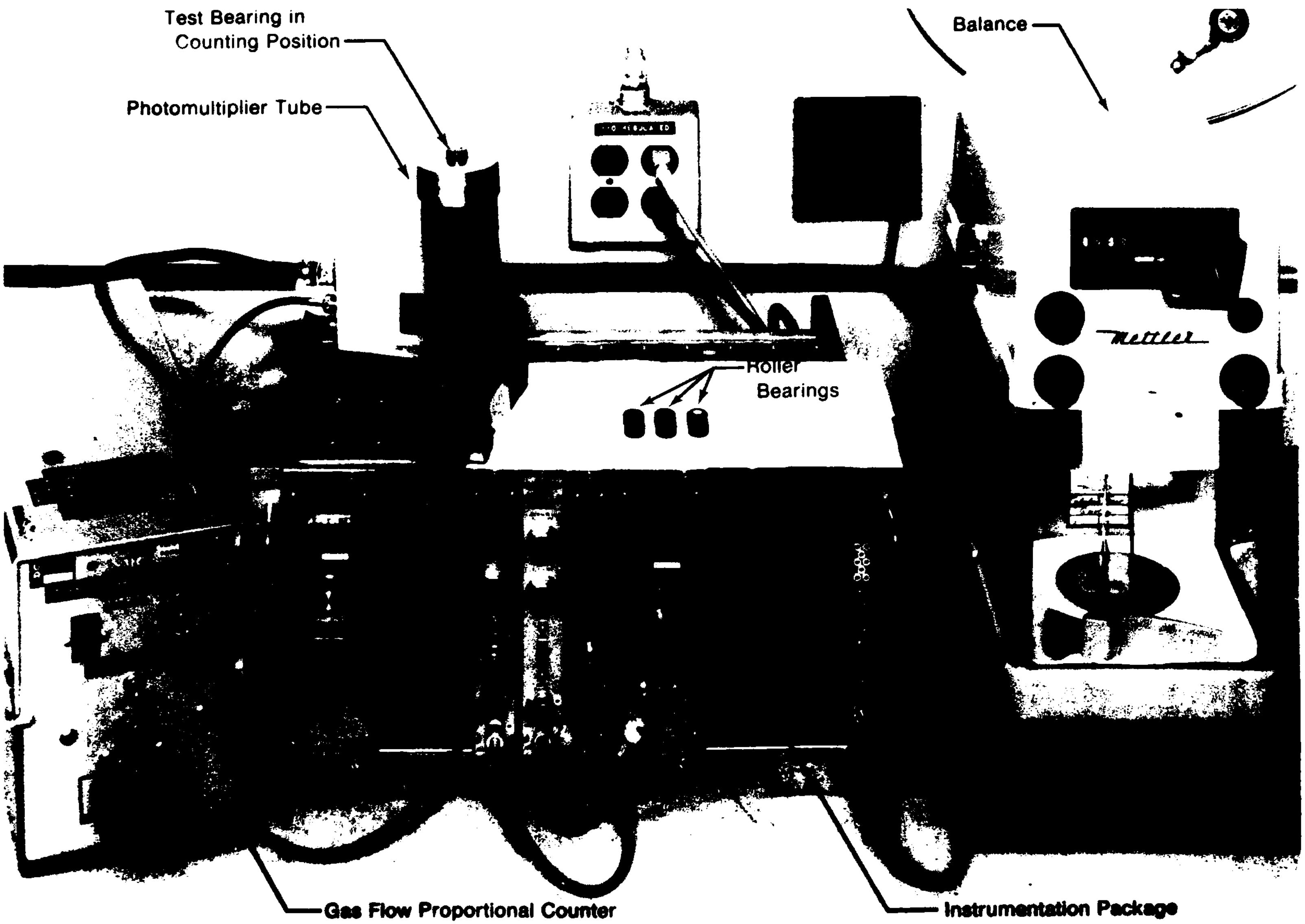

Figure 25. UTRC's Nuclear Measurement Corporation Gas Flow Proportional Counter Detector (40 cpm Background)

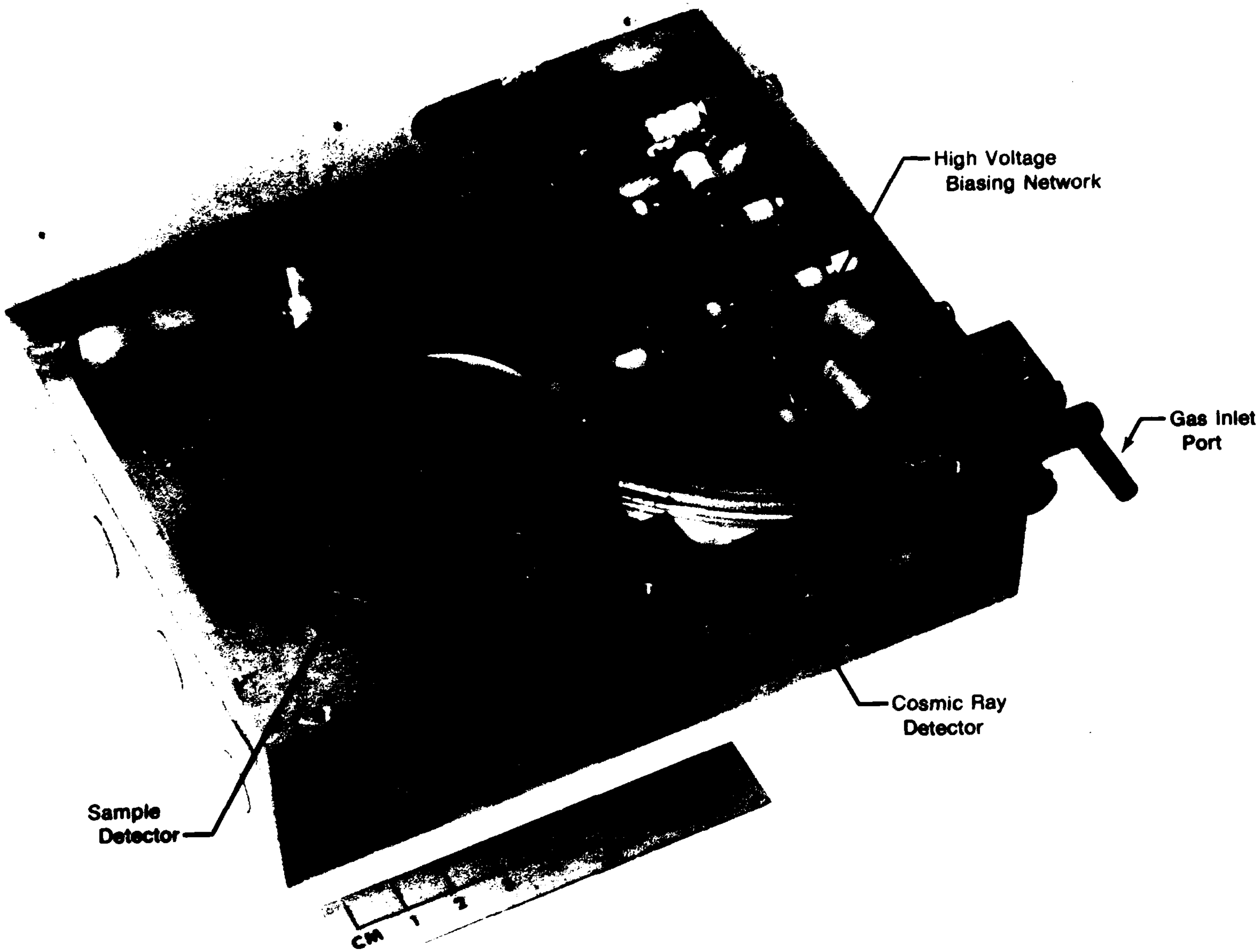

Figure 26. *UTRC's Canberra Corporation Gas Flow Proportional Counter Detector (1 cpm Background)*

There is a trade-off between the instrument's sensitivity to extraneous background counts and its detection efficiency. The smaller the volume of the detector the lower the number of background counts, but the sensitivity for detection also decreases. This program was directed toward using off-the-shelf proportional counters. Further work on optimization of the proportional counter has the potential of improving detector efficiency with a minimal increase in background sensitivity.

3. CALIBRATION STANDARDS FOR OIL-BORNE RADIOACTIVE WEAR METAL DEBRIS

Synthetic wear metal debris standards were prepared from neutron irradiated bearing material drilled from a test bearing No. 1 roller. Known amounts of bearing material were dissolved and reprecipitated as a hydroxide onto a Millipore filter. The standards were counted using the Canberra Industries 2200 gasflow proportional counter. A calibration of 190 counts (50-min counting period) per milligram bearing mass was obtained (Figure 27). The equivalent part per million for a 200-gram oil sample is also illustrated in Figure 27.

4. DEMONSTRATION TEST RESULTS (REFER TO SECTION III)

A. Lubrication System and Oil Sample Collection Considerations

The initial bearing test design assumed a 5-gal oil system (Section IV). The actual testing was performed with a 13-gal oil system. In the actual test system, one part per million represents an oil-borne bearing mass of 46.4 mg. To maintain the 13-gal oil volume, clean makeup oil was added after each oil sample was collected. The dilution effect of removing less than 1% of the total system debris per sample set is negligible with regard to the results obtained from both bearing tests.

B. Radioactive Wear Metal Debris Measurement Results

The Canberra Industries 2200 gasflow proportional counter, calibrated as previously described, was used to measure the amount of oil-borne test bearing radioactive wear metal debris generated during rig testing. Consistent with the device calibration, each oil sample was measured over a 50-min counting period.

Test Bearing No. 1. After 1 hr and 20 min of testing, the debris level reached a 1.6 ± 0.4 ppm concentration level. The trend from 1 hr and 20 min to the end of the 10-hr test program remained essentially stable at the 1.6 ppm level with the precision of the measurement Figure 28.

Test Bearing No. 2. As the shaft speed/load combination was increased from 8000/325 to 10,000 rpm/533.3 lb, the radioactive debris concentration in the oil samples increased from 0 ± 0.25 ppm at 6 hr to 11 ± 0.6 ppm at 10 hr Figure 29.

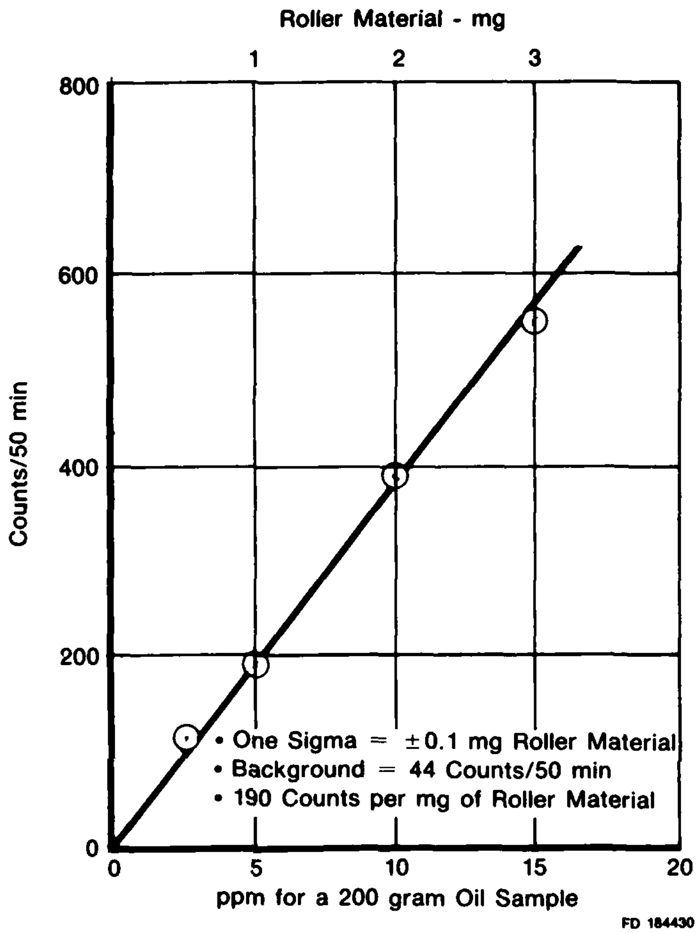

Figure 27. Oil-Borne Radioactive Wear Metal Debris Calibration

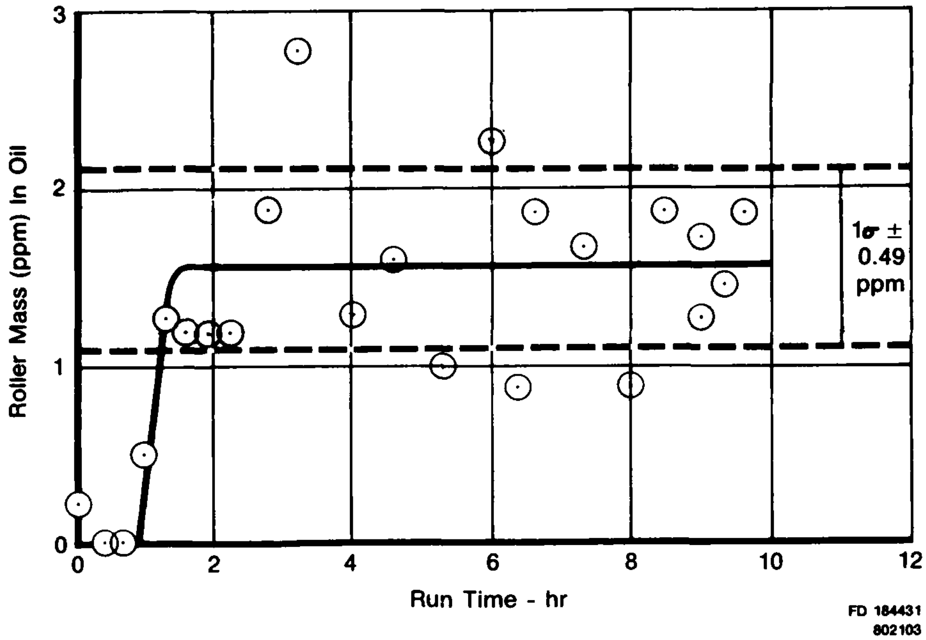

Figure 28. Oil-Borne Roller Debris Mass Determined from Measuring Radioactivity — Unbalanced Roller Test — Test Bearing No. 1

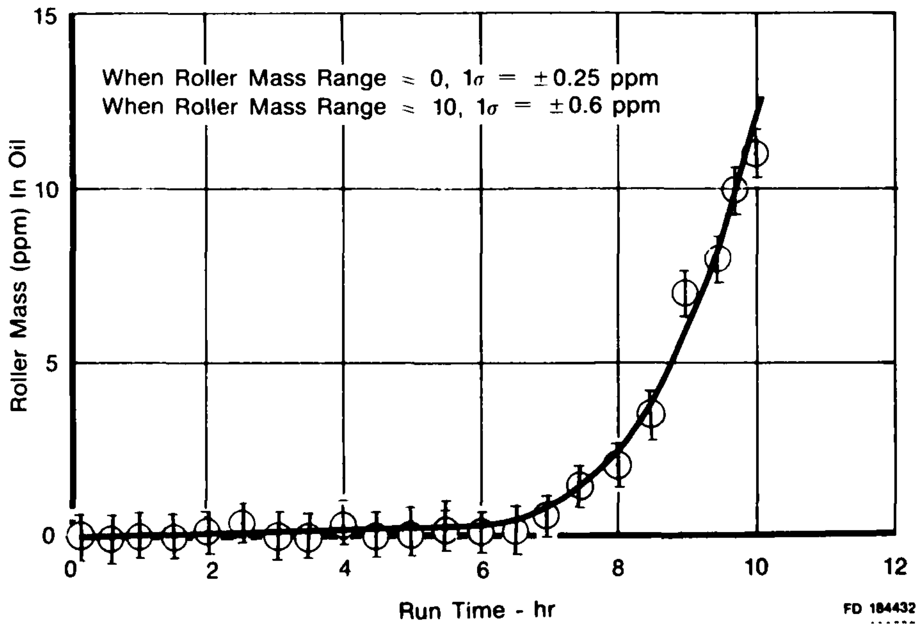

Figure 29. Oil-Borne Roller Debris Mass Determined from Measuring Radioactivity — Increased Roller End Runout Test — Test Bearing No. 2

SECTION VI

NEUTRON IRRADIATION EFFECTS ON METALLURGICAL PROPERTIES

1. SUMMARY

A major concern in regard to neutron irradiation tagging and its acceptability is the need to incorporate an irradiation process which will not affect the metallurgical properties of the M50 bearing steel. Neutron irradiation of the bearing rollers was performed in the reflector of a heavy water reactor at Neely Research Center at the Georgia Institute of Technology. The thermal neutron flux was 1.4×10^{11} n/cm^2-sec, and the fast neutron flux, $E > 0.1$ MeV, was 4.8×10^8 n/cm^2-sec. The maximum irradiation exposure comprised 1 hr and 27 min for a fluence (integrated dose) of 7.3×10^{14} n/cm^2 thermal and 2.5×10^{12} n/cm^2 fast. Such exposure to neutron irradiation is 10^3 to 10^4 times lower than that known to induce changes in the mechanical properties of the steel. This conclusion is supported by both a review of available literature on the subject and by the results of the metallurgical characterization of irradiated M50 bearing steel conducted as a part of this contract.

2. NEUTRON IRRADIATION EFFECTS ON METALLURGICAL PROPERTIES

A. General

Neutrons are uncharged particles which can penetrate the electronic cloud of an atom and interact with the nucleus. If the neutron has sufficient energy, >25 eV, the nucleus can be moved from its position in the lattice, Reference 20. This atomic displacement within the metal structure produces defects that can change the material properties. The amount of energy transferred to the struck atom in an elastic collision is directly related to the energy of the neutron. The "intermediate-energy" neutrons of energies greater than thermal but less than 0.1 MeV, have enough energy to create some damage but are relatively unimportant Reference 21a. Radioactive transmutation of stable iron into radioactive iron-55 results from the thermal neutron flux, (~0.025 eV). Only one atom in 10^{10} atoms of iron becomes radioactive iron-55 at the 0.16 microcurie per gram iron-55 tagging levels used in this program. This level, plus the addition of the other induced radioactivity, is not of any significance with regard to producing material property changes, Reference 21a.

The material properties of metals are greatly dependent upon the dislocations contained in the metal. Dislocations are the result of crystal growth and subsequent manipulation of the solid. These dislocations have the property of being able to move under stress and are reproducible for plastic deformations. Dislocation pinning is one of the most important consequences of the neutron irradiation of metals. The defects introduced by irradiation can pin dislocation, i.e., impede their motion and thereby change the mechanical properties of the metal. In addition, the neutron-induced defects also disturb the periodic atomic arrangement of the metal crystal structure for several atomic distances from the defect. The presence of this disturbance can also affect the mechanical properties of the metal.

Investigations into irradiation effects on structural alloys used in nuclear reactors are directed at fluences ranging from 5×10^{16} n/cm^2 to 1×10^{22} n/cm^2. Charpy impact tests performed on irradiated A212B steel show that *"The specimens irradiated to the low fluence 5.8×10^{16} n/cm^2 ($E > 1$ MeV) can essentially be considered unirradiated materials," Reference21b.* (Note that the bearing rollers were irradiated to a fast fluence of 2.5×10^{12} n/cm^2, a factor of 10^4 lower.) A program to determine irradiation effects on a 19-9DL stainless steel alloy used as a reactor core material was performed over fast fluences ranging from 2×10^{17} to 9.2×10^{20} n/cm^2, $E > 1$ MeV, Reference 21c. Plots of the effects of irradiation on the

yield tensile strength of 19-9DL stainless showed a 72 to 75 ksi yield for the as-received control material, and a 80-90 ksi yield at a fluence of 2×10^{17} n/cm^2. The ultimate tensile strength of the as-received material of 122 ksi showed no change after exposure to a fluence of 2×10^{17} n/cm^2. Effect of irradiation on elongation shows a marked decrease at high fluence levels. For example, materials with an initial elongation ranging from 38 to 45% exhibited an elongation percentage of 37 to 39% after exposure to a fluence of 2×10^{17} n/cm^2. Increasing the fluence to 10^{19} n/cm^2 further reduced the percent elongation to 22%.

Review of other irradiation effect literature shows that most irradiation effect investigations are conducted at fast neutron fluences of above 10^{18} n/cm^2. For the purpose of this program, the 2.5×10^{12} n/cm^2 fast neutron fluence is not considered to have exerted a deleterious material property effect on the tagged bearing roller material.

B. Metallurgical Characterization

Four available M50 steel bearing rollers were utilized as samples for pre- and post-irradiation metallographic characterizations. Due to the destructive nature of these characterization tests, these samples were processed in addition to and at the same low irradiation levels as the complement used for rig testing.

Two of four specimens were selected for evaluation. A flat was ground on the roller face, parallel to the longitudinal axis of one specimen. The prepared flat of that specimen and a transverse face (roller end) of a second specimen were metallographically prepared and etched with Nital. Sufficient material was removed from the specimen to preclude influence on the tests by any surface phenomena.

The post-irradiation microstructure of the rollers was typical of hardened and tempered M50 steel. No changes were noted between the pre- and post-irradiation structures (Figures 31 through 34). The grain size of the specimens was not affected by irradiation (ASTM9 or finer), which complies with the requirement of ASTM7 or finer for M50 steel per P&WA Specification 725. The carbide distribution after irradiation was judged acceptable. Post-irradiation hardness of the specimens taken on polished surfaces was in the range of HRC 59.5-60.4, which falls within the experimental repeatability of the pre-irradiation hardness measurement.

Ten rollers were taken from each of the two test bearing sets and subjected to nondestructive metallurgical and structural characterization inspections. Prior to these inspections all rollers were serialized to permit comparison of pre- and post-irradiation test results.

These inspections consisted of:

a. *Ultrasonic Inspection* — Ultrasonic inspection is used for detecting internal flaws. An ultrasonic wave is reflected whenever a change occurs in the elastic properties of the medium supporting the wave. Medium interfaces such as cracks, inclusions, porosity and voids, as well as the surfaces of a part propagate reflections. Ultrasonic energy resonates between the front and back surfaces of a sample at a rate determined by the elasticity and density of the material. A "sound" material would exhibit regular periodic energy pulses. Succeeding pulses are attenuated by reflection and scattering at the material grain boundaries. This loss is proportional to the grain volume in the material and to the frequency of the ultrasonic pulse. Changes in attenuation may be induced by flaws, internal stresses, or differences in the physical or chemical structure of a material. For the ultrasonic inspection, a setup was made using an Automation Industries 580 main frame with a PR-2 Pulser receiver and a Harrisonic I31006 transducer. Conventional multiple-reflection immersion pulse echo ultrasonic techniques were used for the inspection.

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Figure 30. Prepared M50 Steel Roller Metallurgical Characterization Specimen - Transverse Section — Before Irradiation

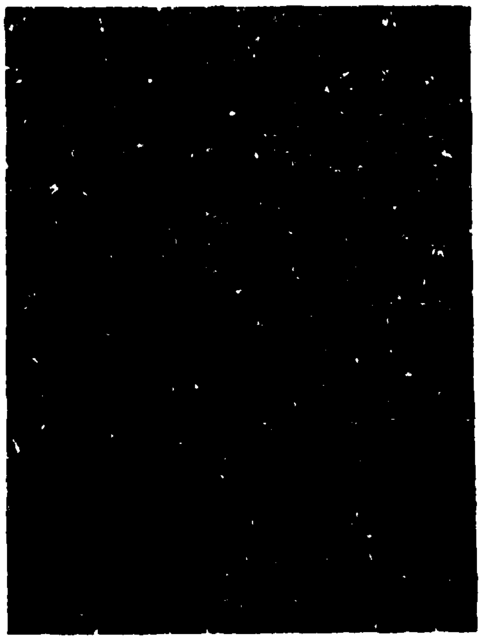

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Figure 31. Prepared M50 Steel Roller Metallurgical Characterization Specimen Transverse Section After Irradiation

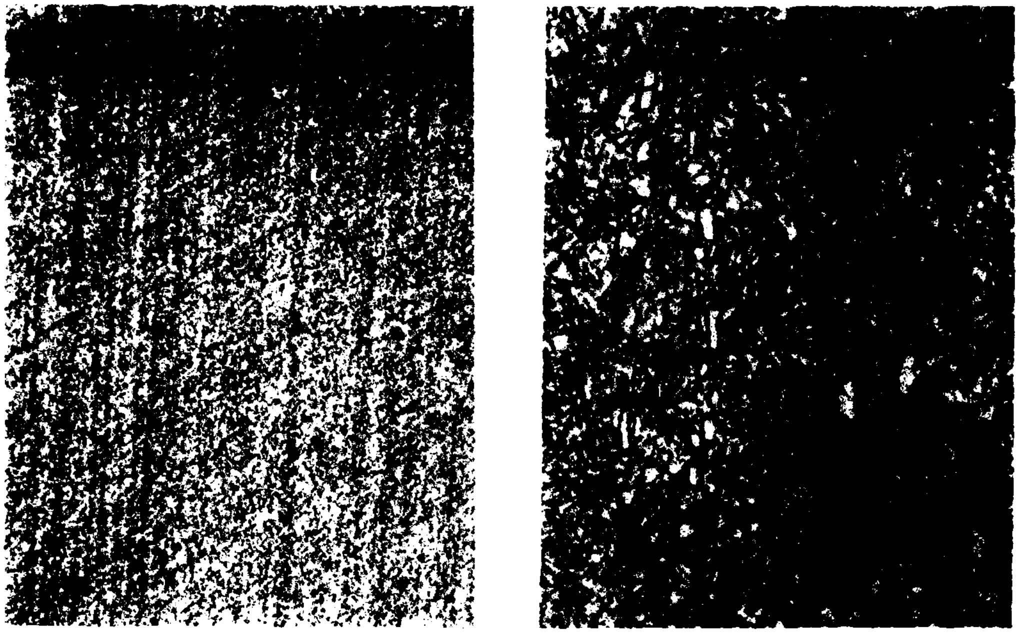

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Figure 32. Prepared M50 Steel Roller Metallurgical Characterization Specimen Longitudinal Section — Before Irradiation

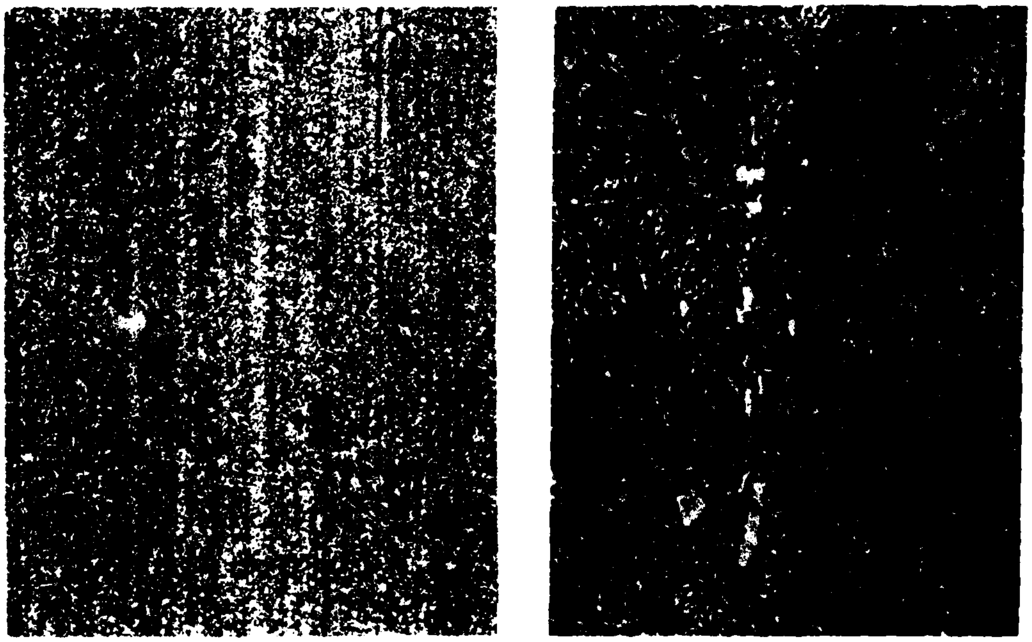

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Figure 33. Prepared M50 Steel Roller Metallurgical Characterization Specimen - Longitudinal Section — After Irradiation

A nonirradiated control M50 bearing steel roller was used to calibrate the equipment for both the pre- and post-irradiation inspections. The equipment was adjusted to display 10 multiples of control roller back-face pulses (Figures 34 and 36).

Using this calibrated setup, 10 rollers from each test bearing were inspected, both before and after the neutron irradiation processing.

Results of the ultrasonic testing showed that the neutron irradiation had no effect on the attenuation constant and signal velocity, thereby supporting the conclusion that grain size and structure are unchanged in the test rollers. Figures 34 and 35 and Figures 36 and 37 are a representative pre- and post-irradiation comparison of one test bearing roller with the control roller.

b. *Eddy Current Inspection* — Eddy current inspection is used to find surface and slightly subsurface material flaws.

Eddy current is defined as a circulating electrical current induced in a conducting article by an alternating magnetic field. As the magnetic field alternates, so does the eddy current. This eddy current flow is limited to the area of the inducing magnetic field.

For the inspection, the test object is placed in the varying magnetic field of a coil carrying an alternating current. The alternating current magnetic field induces eddy currents in the test object. These eddy currents in turn produce an additional alternating current magnetic field in the vicinity of the test object in opposition to the original field.

The flow of eddy current within the test object is affected by the local conductivity of the test object in the area near the test coil. Local conductivity is affected by:

- Lattice distortion/dislocation — in which the location, size or shape of the grain within the material changes.
- Lattice defects — resulting from hardness, stressing or high levels of radiation.
- Discontinuities — such as inclusions, cracks, porosity, affect eddy current flow and cause a decrease in electrical conductivity.

For the eddy current inspection, three elox slots 0.020-in. long by 0.001-, 0.003- and 0.006-in. deep were cut into a control M50 steel bearing roller. This was used to calibrate the measurement system. Figures 38 and 40 illustrate the 0.020-in. long by 0.001-in. deep calibration. The signal from a Forster 2.164 Defectometer with a Creg pencil probe was displayed on a Tektronix 549 storage oscilloscope. The rollers were held by a collet in an 8-in. lathe adjusted to turn at 260 rpm. Ten rollers from each test bearing were inspected (Figures 39 and 41), both before and after irradiation.

Referring to Figures 38 through 41 the periodic sinusoidal baseline is a normal indication. Surface or slightly subsurface grain boundary breaks or other discontinuities of the material would appear as sharp spikes, similar to that produced by the eloxed slots in Figures 38 through 40.

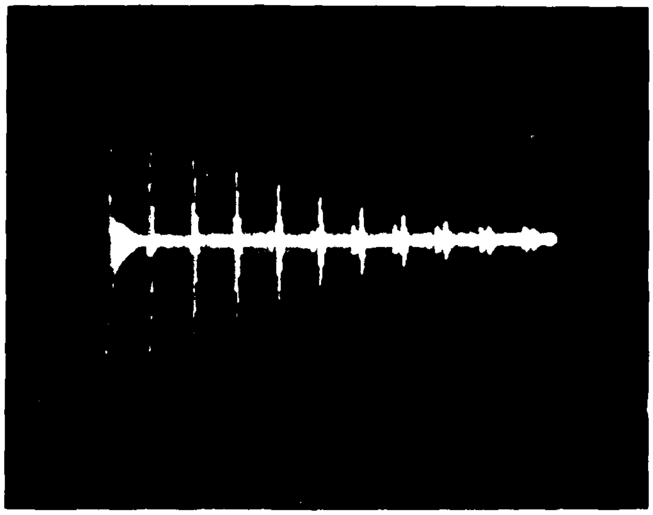

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Figure 34. Ultrasonic Pulse Echo from Master Roller, Showing 10 Multiples of Back Faces, April 1979

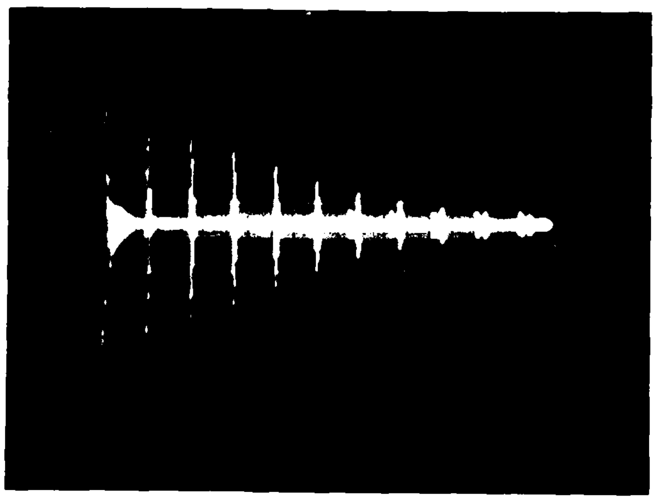

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Figure 35. Ultrasonic Pulse Echo from Sample B-1 Bearing Before Irradiation Showing 10 Multiples of Back Faces, April 1979 (Same Test Setup as in Figure 34)


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Figure 36. Ultrasonic Pulse Echo from Master Roller, Showing 10 Multiples of Back Faces, October 1979


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Figure 37. Ultrasonic Pulse Echo from Sample B-1 Bearing After Irradiation Showing 10 Multiples of Back Faces, October 1979 (Same Test Setup as in Figure 35)

FD 189272

Figure 38. Eddy Current Trace Over Elox Slot (0.001 in. Deep × 0.020 in. Long) in Master Roller at 260 rpm, April 1979

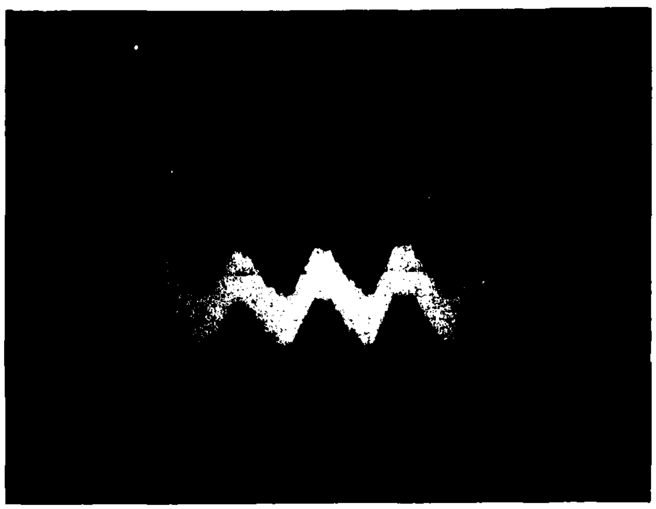

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Figure 39. Eddy Current Trace from Sample A-7 Bearing at 260 rpm Before Irradiation, April 1979 (Same Test Setup as in Figure 38)

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Figure 40. Eddy Current Trace Over Elox Slot (0.001 in. Deep $\times$ 0.020 in. Long) in Master Roller at 260 rpm, October 1979

FD 189271

Figure 41. Eddy Current Trace from Sample A-7 Bearing at 260 rpm After Irradiation, October 1979 (Same Test Setup as in Figure 40)

Because of improper handling and storage between the pre- and post-irradiation testing, some corrosion pitting took place on the control roller. This can be seen in the secondary spiking in Figure 40. There is similar corrosive action on the test rollers following irradiation, but to a much lesser degree. The discolored spots from this corrosion were more predominant on test bearing No. 2 rollers, but were noted on both sets. A typical indication of these discolored spots can be seen in Figure 41. Based on the calibrated spike of the 0.001-in. deep elox slot in Figure 40, this indication represents a depth of 0.000025 to 0.00005 in.

Aside from the localized corrosion, the eddy current inspection indicated no apparent differences between the pre- and post-irradiated rollers.

c. *Fluorescent penetrant inspection* — The 10 rollers from each test bearing set were processed with ZL-35, and subjected to ultra high-sensitivity, post-emulsification, fluorescent penetrant inspection. This inspection is used to find flaws open on the surface and provided no additional information.

3. CONCLUSION

All nondestructive and destructive metallurgical characterization testing, as well as available literature, indicate that no metallurgical or structural changes in the M50 material were induced as a result of the low-level irradiation tagging technique.

SECTION VII

RADIATION SAFETY

1. NEUTRON IRRADIATION BEARING TAGGING

A. General

Neutron irradiation of the roller bearings produce essentially uniform distribution of the radioactivity throughout the roller structure. In terms of the Iron-55 radioactivity, approximately one Iron-55 atom is present per 10^{10} nonradioactive atoms. The uniform distribution and the low X-ray energy (5.9 keV) emitted by Iron-55 results in self-absorption of 97% of the emitted X-rays within the roller material. The predominant sources of significant dose producing radiation immediately after neutron irradiation are from Chromium-51 and Iron-59. Radioactive decay reduces the Chromium-51 by 99% and Iron-59 by 94% 6 months after neutron irradiation (Table 4). The radiation dose contribution by Cobalt-60 is directly related to the weight percent of the cobalt contamination present in the master melt (Table 1). Cobalt-60 gamma-ray emissions of 1,170 and 1,330 keV readily penetrate the bearing material and the 5.2 year half-life preclude any effects of radioactive decay.

B. Radiation Measurement Prior to Bearing Set Assembly

The relative intensities of the gamma-ray emitted from a single roller irradiated on 18 June 1979, and measured by a germanium detector, Figure 3, indicate the predominant Chromium-51 and Iron-59 radioactivity after 117 day decay. The radiation dose rate from an unassembled bearing roller set, 32 rollers, when positioned in contact with the 3.5 inch diameter sidewalls of an air ionization chamber of a Victoreen-440 dose rate meter was 3.2 millirem per hour. To determine the shielding effects of the 0.062 in. thick phenolic plastic wall, the dose rate was also determined by positioning 8 rollers in contact with the 0.01 in. thick mylar end window of the ionization chamber. The dose rate was 0.9 mrem per hr or about 10% higher per roller.

C. Radiation Measurements After Bearing Rig Testing

The low levels of gamma radiation after 8 months decay is evident from a comparison of ambient background and the gamma emissions from a single roller, Figure 43. The Cobalt-60 1,170 and 1,330 keV gamma rays are the most prominent emissions from the roller; but the Cobalt-60 gamma-ray intensity is equivalent to the 1,461 keV emission from naturally occurring Potassium-40, Table 14. The radiation dose rate from an unassembled bearing roller set (32 roller) when positioned in contact with the side wall of the Victoreen-440 ionization chamber measured 0.7 millirem per hour. The radiation levels from an assembled bearing were below the measurable range of the ionization chamber and in order to obtain an estimate of dose rate a geiger-muller Eberline RM-3A count rate meter was used (Figure 44). Ambient bakground is in the range of 0.01 to 0.02 millirem per hour and under ambient conditions this yields 100 counts per minute on the geiger counter. The radiation levels from an assembled bearing, Figure 44, measure 950 counts per minute or 9.5 times ambient background (less than 0.2 millirem per hour). At a distance of 6 in. from the assembled bearing the dose rate was about twice normal background. For comparison, the radiation dose rates and radiation doses from natural sources and from medical X-ray are given in Table 15.

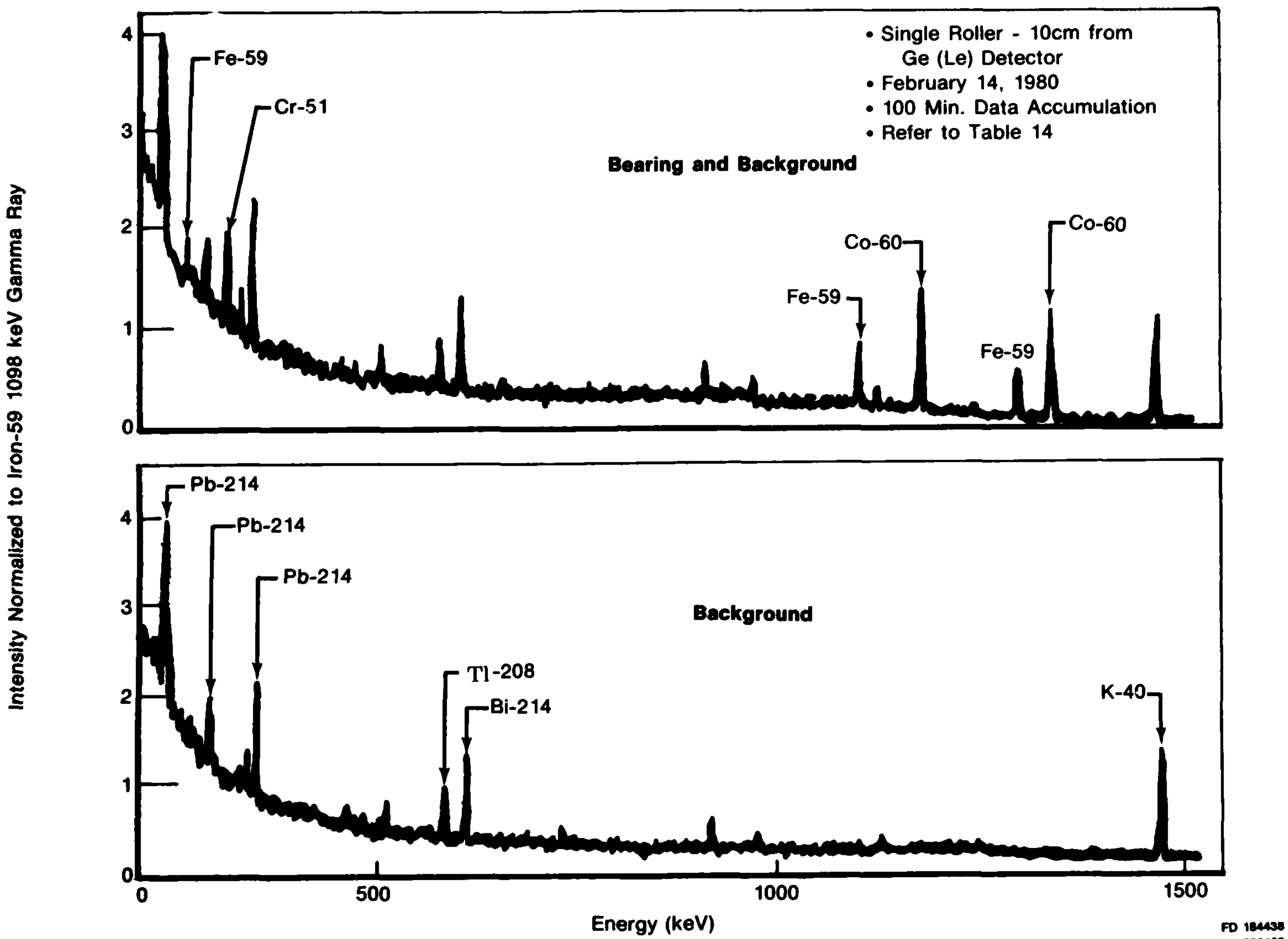

Figure 42. Spectra of Natural Gamma Radiation from Background Sources and Gamma Radiation from a Neutron Activated Bearing Roller After Eight Month Decay

TABLE 14. AMBIENT GAMMA RADIATION BACKGROUND AND GAMMA RADIATION EMITTED FROM NEUTRON ACTIVATED ROLLERS

	Radioactivity		
Gamma Energy (keV)	*Natural Background*	*Neutron Activated Roller*	*Laboratory Source*
143		Iron-59	
193		Iron-59	
242	Lead-214		
295	Lead-214		
320		Chromium-51	
352	Lead-214		
517			Kryton-85
583	Thallium-208		
609	Bismuth-214		
1098		Iron-59	
1170		Cobalt-60	
1290		Iron-59	
1330		Cobalt-60	
1461	Potassium		

TABLE 15. RADIATION DOSE RATES AND DOSES FROM COMMON SOURCES

	Dose (mrem/hr)	*mrem*
Potassium-40 naturally occurring in the body*[1]	0.002	20 per year
Natural background dose at sea level (average)[1]	0.011	100 per year
3-hr jet-plane flight[1]	0.67	2 per flight
Chest X-ray Source	—	30 per exposure
Dental X-ray single exposure[2]	—	250-450 per exposure

[1]Reference 22
[2]Reference 23
*0.0118 percent of all potassium is potassium-40

D. Handling Procedure for Neutron Tagged Bearings

In handling the individual rollers used in the test program, the skin contact dose rate was sufficiently low to represent an inconsequential radiation exposure. No special handling requirement was necessitated when working in direct contact with either individual rollers or with an assembled bearing. In compliance with federal regulations, groups of 16 rollers required a radioactive material label; less than 16 rollers did not. The label showed an Iron-55 isotope with an amount of 4 microcuries per roller and a date; the back of the tag stated that no special handling was required.

The radiation levels could be increased by a factor of 10 over those used for the radioactive tag demonstration testing without imposing excessive restrictions on the handling of the rollers or the assembled bearing. Simple precautions such as posting signs limiting the direct skin contact time and the use of physical barriers such as large cardboard boxes for bearing storage would be required.

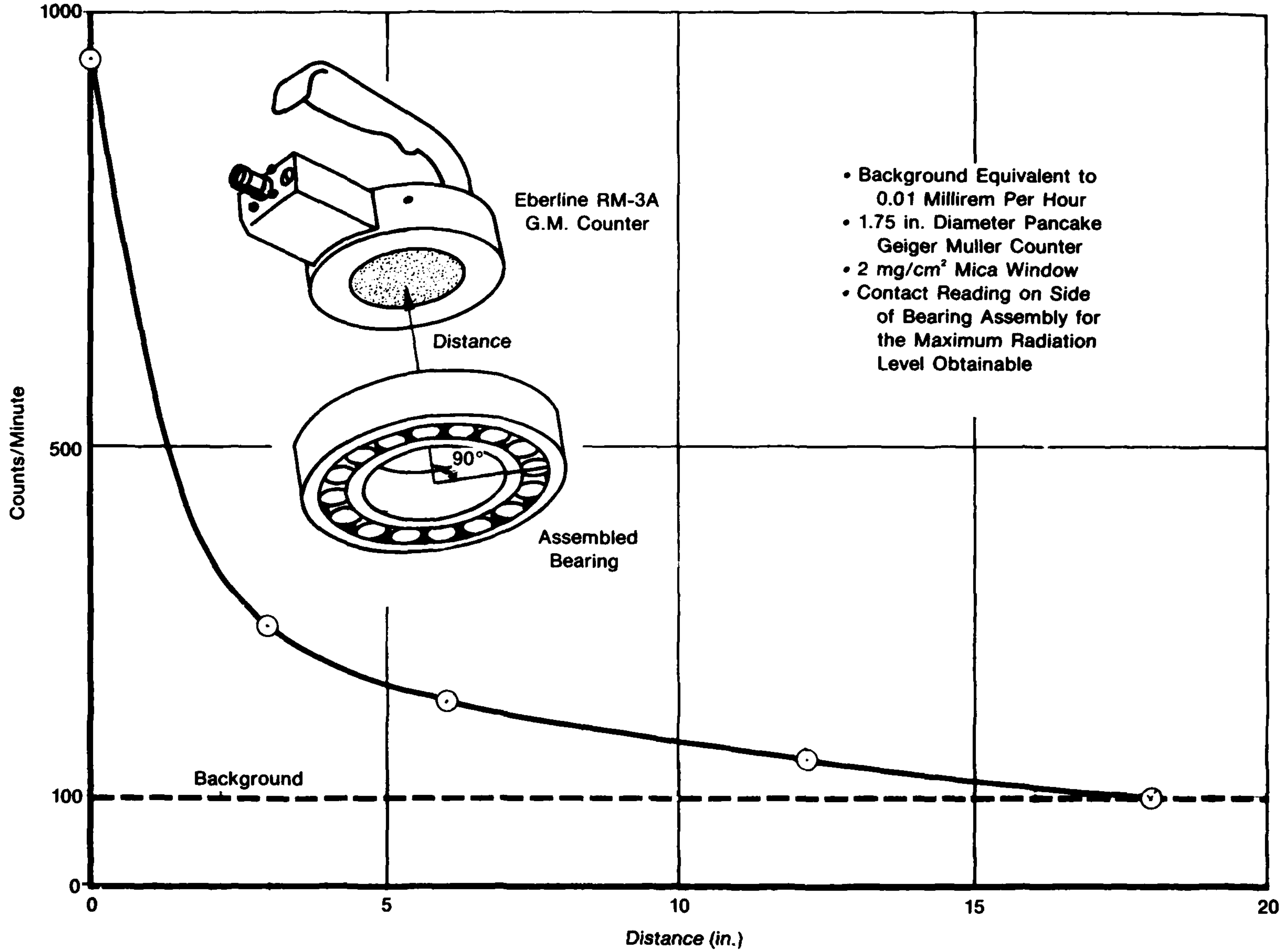

Figure 43. Radiation Dose Rate from a Neutron Tagged Assembled Bearing

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2. CONCLUSION

The radiation safety procedure required to inspect, assemble into bearings, store, ship and install assembled bearing into engines using neutron irradiated bearing rollers are minimal or none. The impact on the normal roller handling procedures occur only during the visual inspection of the roller after tagging, i.e., inspector must be made aware that the rollers are radioactive. For the neutron irradiated bearing the finger skin contact dose rate after 6 months is 0.12 mrem per hour from a single roller and 0.8 mrem per hour from an assembled bearing, Table 16.

TABLE 16. ROLLER BEARING DOSE RATE FROM NEUTRON IRRADIATION

Time From Initial Irradiation (month)		*Contact*[1] *(mrem/hr)*	*3 in. (mrem/hr)*	*1 ft (mrem/hr)*
4.5	One Roller	0.11	0.01	
	Assembled Bearing[2]	0.8	0.2	0.14
6	One Roller[3]	0.06		
	Assembled Bearing[2]	0.4	0.1	0.07
8	One Roller	0.02		
	Assembled Bearing	0.17	0.04	0.03

[1] Contact to air cognization chamber of a Victorian 440 dose rate meter. The Skin contact does rate is estimated at 2 times the meter contact dose rate.
[2] Assembled bearing dose rate were determined from Figure 43. Values at 4.5 and 6 months were calculated from dose rate at 8 months.
[3] Single roller dose rate at 6 months were calculated from measured dose rates at 4.5 and 8 months.
● Natural radiation background 0.01 to 0.02 (mrem/hr)

SECTION VIII

GOVERNMENT REGULATIONS

An important consideration in the evaluation of radioactive bearing tags is the federal regulatory requirements for the handling and disposal of low level radioactive material. Regulations for the use and possession of radioactive byproduct materials, (i.e., any radioactive material yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material, fission of uranium) are promulgated by the U.S. Nuclear Regulatory Commission (Reference 4). Both P&WA and UTRC are licensed in the use of radioactive materials for performing research and development work.

The Nuclear Regulatory Commission provisions exempting the research and development user from compliance with the standard regulations in regard to certain specified quantities of radioactive material exist. These exempt quantities[1] of radioactive material are not considered environmentally significant.

The microcuries of radioactivity for the radioisotopes used for tagging the bearing rollers 6 months after irradiation approach the exempt category (Table 17). The total radioactivity exceeds the exempt category by a factor of 2.1.

Specific exemptions from the requirements regulation (Section 30.11 and Parts 31-35) may be granted by the Commission upon application of any person or upon its own initiative.[2]

Table 18 lists some of the items being granted exemptions. It can be noted that levels significantly higher than the exempt quantity have been authorized.

TABLE 17. EXEMPT QUANTITIES OF RADIOACTIVE MATERIALS

	Schedule B[(1)] *(μCi)*	*Radioactivity at the Start of the Test*[(2)] *(μCi)*	*Quantity Comparison Factor*[(3)] *Neutron Activation*[(4)]
Iron-55	100	113	1.13
Iron-59	10	4.6	0.46
Cobalt-60	1	0.46	0.46
Chromium-51	1,000	12.8	0.03
Total		130.9	2.08

[(1)]NRC regulations (30.71)
[(2)]Activity at the test program occurs 6 months after neutron activation
[(3)]The quantity comparison factor is the isotope activity/Schedule B
[(4)]Neutron radioactivity values were obtained from Table 6

TABLE 18. SUMMARY OF EXEMPT ITEMS

Radioisotope	*Devices*	*Per Device Microcuries*	*Schedule B Microcuries*
Krypton-85	Electron tubes	30	100
Promethium-147	Self-luminous timepiece	200	10
Hydrogen-3	Marine compasses	750,000	1,000
Strontium-90	Ion detection devices	50	0.1
Cobalt-60	Spark gap tubes	1	1

In petitioning for an exempt product status, a positive cost benefit relationship must be demonstrated. It must be shown that the product in question is required and that the need for this product cannot be satisfied through the utilization of nonradioactive product material. In addition, an environmental report incorporating appropriate safety analyses and verifying that the product is safe under all possible conditions of use must be compiled and submitted. Reference 24, as well as the NRC rules themselves, details the Environmental Report Requirements.

The only NRC regulation mandated during the installation and realization of the Task IV test program was the affixing of a "CAUTION RADIOACTIVE MATERIAL" tag on the box containing the bearings. During rig operation, the tag was attached to the rig itself. The radioactivity of the debris generated and collected during the rig testing was of sufficiently low levels to warrant an exempt status from all regulations (NRC Section 30.14 Exempt concentrations, "Any person is exempt from the requirements of a license for material containing byproduct material in concentrations not in excess of those listed in 30.70 Schedule A.").

Both the exempt concentrations and the debris level concentration of the tests undertaken are presented in Table 19.

Additionally, inventory control of the radioactively tagged hardware must be maintained.

[1] Exempt quantities are defined in Chapter 30 Paragraph 18 of NRC Rules and Regulations, "Any person is exempt from the requirements of a license to the extent that such person receives, possesses, uses, transfers, owns, or acquires by-product material in individual quantities each of which does not exceed the quantity set forth in 30.71, Schedule B." In addition, Section 32.19, states that no more than 10 exempt quantities set forth in 30.71, Schedule B, shall be sold or transferred in any single transaction. For the purpose of this requirement, an individual exempt quantity may be composed of fractions of one or more of the exempt quantities in 30.71, provided that the sum of such fractions shall not exceed unity.

[2] The exemptions are authorized by law provided they will not endanger life or property or the common defense and security and are otherwise in the public interest. Part 32 of the regulations "Specific Domestic Licenses to Manufacture or Transfer Certain Items Containing By-Product Materials" prescribes requirements for the issuance of specific licenses to persons who manufacture or initially transfer by-product material for sale or distribution to persons exempted from the licensing requirements.

TABLE 19. EXEMPT CONCENTRATIONS OF RADIOACTIVE MATERIALS

		Test Program[(1)]	
	Schedule A[(2)] *($\mu Ci/ml$) or ($\mu Ci/g$)*	*$\mu Ci/ppm$*[(3)] *of Wear Debris*	*$\mu Ci/ml$*[(4)] *of Oil Per ppm*
Iron-55	8×10^{3}	2.5×10^{-3}	1.3×10^{7}
Iron-59	6×10^{4}	1.1×10^{4}	5.8×10^{9}
Cobalt-60[(5)]	5×10^{4}	$7.2 \times 10^{4}/1.03 \times 10^{5}$	$3.8 \times 10^{8}/5.4 \times 10^{10}$
Chromium-51	2×10^{2}	2.9×10^{4}	1.5×10^{8}

[(1)] Refers to wear metal debris removed from the bearing and distributed in 5 gal

[(2)] NRC Regulations (30.71)

[(3)] The radioactivity in the oil system per ppm of bearing wear

[(4)] The radioactive concentration per ml of oil

[(5)] Max concentration of cobalt in M50 (2500 ppm)/actual test concentration (25 ppm)

SECTION IX

LIFE CYCLE COST BENEFITS

1. INTRODUCTION

Presently, engine lubricants are routinely analyzed by the USAF to detect incipient breakdowns in the oil-wetted sections of turbine engines. Evaluation of the liberated metal wear debris in the oil permits the removal of an engine prior to the occurrence of secondary damage. The engine condition monitoring method employed to conduct these analyses, the Spectrometric Oil Analyses Program (SOAP), has provided a valuable means of measuring wear metal concentrations in the engine's lubricating oil. However, SOAP analysis does not identify the wear location in the engine. Thus, extensive engine inspection of nearly all oil-wetted engine parts is required for identification of the damaged component. A wear metal identification system that diminishes the extent of teardown results in reduced maintenance costs and out-of-service time.

The incorporation of the neutron irradiation tagging technique of key engine high-speed main shaft bearings, in conjunction with SOAP analysis, could not only detect high metal wear rates but could pinpoint the location of problem bearings.

2. GENERAL

The radioactive tagging technique is applicable to any engine/bearing system. As part of the development program, a life cycle cost estimate was conducted. It compares acquisition costs for the tagging technique with the savings of operational/support costs of the neutron irradiation tagging methods as they are applied to the selected engine bearing system discussed in Section III.)

Acquisition costs include research, development and procurement expense, while operational costs comprise parts usage and associated maintenance expenditures.

Increasing the activity level up to ten times the levels used in this program would cause insignificant additional irradiation, handling and safety expenditures (and risks, refer to Section VII). However, the resulting higher sensitivity has the potential to significantly increase the cost savings by expanding the margin of detectability of tagged bearings experiencing above normal wear.

Incorporation of the tagging technique does not affect the weight, reliability or performance of the engine/bearing system.

A. Engine Maintenance Costs

The chargeable unscheduled engine removals (UER's) used in this study were extracted from the Air Force maintenance data collection system (66-1). Only those UER's associated with either a SOAP indication of high iron or with iron chips on the chip detectors were utilized in this analysis.

It was assumed that the historical UER rate per 10^3 engine flight hours would apply over the 15-yr Life Cycle Cost analysis defined in this study. These UER rates were also assumed to be equally applicable to both advanced USAF aircraft used in this LCC study.

The cost savings in maintenance man-hours (MMH) expended at the depot level was derived by determining the difference in MMH between:

a. Current practice without the capability to isolate the specific discrepant bearing compartment.

b. Proposed Isotope technique which identifies the specific discrepant bearing compartment.

The Maintenance man-hours (MMH) for (a) and (b) above were determined from the following sources:

a. Current maintenance practice MMH's were defined by engines processed through P&WA/GPD for bearing compartment incidents. Average MMH's for these engines were taken directly from P&WA/GPD reports. These MMH's represent expenditures incurred when the discrepant bearing compartment cannot be positively identified.

b. The MMH's used for engine maintenance incorporating the Isotope technique, which identifies the specific discrepant bearing compartment, were based on P&WA/GPD's Maintenance Task Times Listing for the selected engine generated by maintainability analysis. This listing defines the MMH's required to remove and replace a specific bearing.

B. Acquisition Costs of Radioactive Tagging Technique

For this program small sample lots of bearing rollers and material were irradiated and analyzed. In order to incorporate the neutron irradiation tagging technique in the selected engine, additional developmental costs associated with larger lot size have been anticipated and assumed in the acquisition costs. These costs would include fixturing and roller processing prior to irradiation and radiological oil analysis procedures. Also included were the added costs associated with:

- A liaison effort between the Air Force, the Nuclear Regulatory Commission and P&WA.
- Added documentation and record storage tasks.
- Written procedures/personnel training costs.
- Used radioactive bearing material disposal costs.

The cost development assumes the reactor will process 12 bearings at a time and that bearings would be available in lots of 48 for neutron irradiation processing.

The acquisition costs are weighted by a development/experience benefit, which would reduce the cost of the second lot of bearings by 30% of the initial lot costs. The cost of all subsequent lots would be reduced by 35% of the initial lot. Program results indicate that each bearing will require two irradiation operations during its useful life (15 yr).

C. Additional Ground Rules

Aircraft Type	A	B
Total Number Engines	1614	1563
Effective Flight Hour (EFH) per Year per Operational Eng.	288	272
Depot Labor Rate* $/MMH	32.34	32.34

*Constant 1980 dollars per U. S. Air Force Life Cycle Costs Group Resources Management Division, Wright-Patterson AFB, 20 December 1979.

3. COSTS SUMMARY

Acquisition Δ Costs	A	B	Total
● Tagging of Bearings Production Engines	+2.76M	+2.80M	+5.56M
● Spare Parts	+0.74M	+0.74M	+1.48M
● Radiological Oil Analysis	+0.06M	+0.06M	+0.12M
● Recovery/Disposal of Radioactive Materials	+0.02M	+0.02M	+0.04M
Maintenance Δ Costs			
● Repair Labor Savings	−5.69M	−5.58M	−11.27M
Δ Life Cycle Costs	−2.11M	−1.96M	−4.07M

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

The radioactive bearing tagging technique developed in this program is a diagnostic system to identify and locate engine bearings experiencing above-normal wear rates. This incipient wear detection technique complements advanced engine modularization by confining engine teardown to the specific bearing compartment experiencing the problem.

Analyses of various radioactive tags resulted in selecting the isotope, iron-55, to best meet all technical requirements. The linearity between nuclear counting and the parts per million concentration of iron-55 in oil provides an ideal means of recognizing bearing distress and assessing the amount of bearing roller material loss. In addition, it was determined that membrane filtration and gas flow proportional counting constitute the best technique for wear debris extraction and counting.

The neutron irradiation tagging technique was evaluated in a simulated gas turbine engine bearing environment. Test results showed that the tagging method would provide a means of identifying and locating a tagged engine roller bearing experiencing abnormal wear.

The radioactivity levels at the start of rig testing were established according to the neutron activation calculations for M50 bearing steel (Table 6). Increasing the radioactivity levels by a factor of 4 to 10 times over that used in the demonstration tests (Table 6) would not require special handlinng requirements when working in direct contact with either individual rollers or with an assembled bearing but would extend the useful bearing tag life from 5 to a minimum of 10 years.

The metallurgical characterization testing performed as a part of this program has shown that no metallurgical or structural change in the M50 material was induced by the tagging process. Additionally, available literature indicates that the test bearings used in this program were exposed to a neutron irradiation level of 10^3 to 10^4 times lower than that known to induce changes in the mechanical properties of steel.

The life cycle cost benefit study conducted as a part of this program indicates a cost savings of over 4 million dollars when the technique is applied to a single bearing in a typical advanced engine/bearing system (based on a 10 year tag life).

As part of further evaluation of the bearing tagging technique it is recommended that:

- The neutron irradiation tag presented here be subjected to long term evaluation in a full scale rig and experimental engine lubrication system.

- The krypton impregnation tagging technique be further evaluated as a second tagging source in applications where its particular properties could be utilized i.e., in the cages of other bearings or the vanes in fuel pumps.

The current program established that the tagging technique does not require special handling procedures in a gas turbine engine maintenance environment. It is recommended that more extensive evaluation of the methods herein presented be conducted with the Air Force operational and safety groups prior to tag incorporation.

In summary, the program results indicate that the neutron irradiation tagging techniques will permit the detection of incipient bearing failures, as well as, provide information as to the location of such distress. Such results will, moreover, be achieved with safe low-level radioactive methods, and with a net savings in life cycle costs.

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